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EDITOR-IN-CHIEF'S WORD

Dear Readers,

In the new issue of Engineering Power, we continue our focused exploration of energy planning and energy efficiency - a theme that has been at the core of our past two editions. The importance of these topics cannot be overstated. Energy planning is a cornerstone of the ongoing transition toward sustainable and resilient energy systems, particularly in remote and insular regions. At the same time, improving energy efficiency remains a fundamental challenge, requiring both technological advancements and strategic innovation. In this issue, our contributors explore innovative strategies for optimizing energy use and planning sustainable systems for the future. These studies not only expand on the discussions from our previous editions but also offer fresh insights and forward-thinking solutions. We thank the authors and reviewers for their contributions and trust that you will find this issue both informative and inspiring.

Editor-in-Chief
Vedran Mornar, President of the Croatian Academy of Engineering

EDITOR'S WORD

Dear Readers,

The third and last issue of the journal Engineering Power, edited by Prof. Sandro Nižetić, PhD and Assoc. Prof. Goran Krajačić, PhD, is in front of you. The theme of this issue is energy planning and energy efficiency. The three articles cover the areas of improving energy efficiency in existing buildings, digital twin models with ESG methodology as a tool in the case of the tourism sector and two-level energy planning approach for smart islands. I hope you enjoy reading this issue.

Editor
Bruno Zelić, Vice-President of the Croatian Academy of Engineering

FOREWORD

The key aspect of energy transition is related to energy planning, which is nowadays one of the hot topics in the research community. The key obstacles related to energy planning are directed to the level of energy interconnectivity between countries, local and regional renewable energy capacities and suitable balancing strategies. The most demanding areas for energy planning are remote areas since they are usually not well connected with the mainland and become very challenging for energy planning. The final goal of energy planning is to develop smart and resilient low carbon energy systems. Besides energy planning, energy efficiency also plays a pivotal role in energy transition goals. Namely, various existing technologies, processes or systems need to be improved in terms of energy efficiency to minimize energy demands and by that to also reduce harmful impacts to the environment. Different engineering solutions need to be further refined with respect to energy efficiency and followed by novel approaches.

This special issue brings new knowledge in the field of energy planning and energy efficiency, it consists of overall three published papers. In the work Enhancing Energy Efficiency in Existing Buildings: Overview of an Innovative Forecast Control Approach for Hydronic Heating Systems, authors were focused on the forecast control systems in building heating applications. Novel proposed forecast control system represents a cost-effective solution that offers quality alternative to the traditional weather-based controllers, and that can for sure improve energy efficiency of buildings. The proposed control approach was successful in the case of the building heating system, however implementation in HVAC systems will be more challenging, mainly due to different control protocols and which is part of future research. The digital twin's strategy combined with ESG principles (Environmental, Social, and Governance) was analyzed in paper ''Digital Twin Models with ESG Methodology as a Tool for Transforming Solutions in the Transport-Energy Sector with Applications to Sustainable Tourism''. The focus of the work was to implement a previously mentioned approach in the case of the tourism sector. The results revealed that proposed combination of digital twins, coupled with ESG, can improve sustainability in tourism, mainly by optimizing transportation energy and use. Some practical challenges were also discussed as well as necessary adoption actions. The specific energy planning approach was discussed in the paper ''Two-level energy planning approach for smart islands energy systems development''. The work was generally focused on island's energy systems where local needs, as well as available resources were carefully considered, together with examined security of electric power systems. Several energy planning scenarios were analyzed within the work and modelled to reach a 100% energy self-sufficient island of Vis as case study. Key outcomes of the work clearly indicated that island's energy system can become almost self-sufficient in terms of needs for electricity and transportation. Results are encouraging more firm actions towards the development of smart and resilient low carbon island energy systems. Previously briefly elaborated papers in this special issue provided novel approaches that are contributing to the energy planning and energy efficiency topics.

The Guest Editors would like to thank the authors for their contribution as well as to the anonymous reviewers who have helped to improve the quality of published papers. Finally, we would like to thank Prof. Dr. Bruno Zelić for providing us with technical support for managing of this special issue.

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Sandro Nižetić, University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture
Goran Krajačić, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

CONTENT

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Enhancing Energy Efficiency in Existing Buildings: Overview of an Innovative Forecast Control Approach for Hydronic Heating Systems

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Abstract

Globally, there is a strong focus on using modern technologies to reduce carbon footprint and increase the energy efficiency of buildings. Achieving carbon-neutrality in EU by 2050 requires prioritizing energy efficiency improvements in current buildings through widely applicable and field-verified methods. This article describes a forecast control system that uses simple correlations with data from online weather predictions, including changes in wind speed, outdoor temperature, and solar insolation to optimize heating conditions. The presented method incorporates the building's actual energy model of the installed heating system, user behavior (preference profiles), and weather conditions forecasts. The implementation of presented in this article forecast control of heating system can result in energy savings of an average of 13.4% energy in residential buildings and 10.7% in public buildings compared to traditional systems, with a payback period of about 0.6 heating seasons. Installing this system in existing buildings takes less than 2 hours and poses no challenges for users or facility managers. Forecast control of heating systems can be particularly valuable for existing buildings due to their low cost and ease of implementation because it can be easily integrated with existing weather-based control systems.

***Keywords**: forecast control, energy efficiency in buildings, space heating control, model predictive control, building heating system management, hydronic heating system*

1. Introduction

According to International Energy Agency, building operations constitute 30% of global final energy consumption and 26% of energy-related emissions [1]. The implementation of minimum performance standards and building energy codes is expanding in scope and stringency across countries. Concurrently, the adoption of efficient and renewable building technologies is accelerating. Despite these positive trends, the sector requires more rapid advancements to meet the Net Zero Emissions by 2050 (NZE) Scenario. This decade is crucial for implementing necessary measures, aiming for all new buildings and 20% of the existing building stock to be zero-carbon-ready by 2030 [2][3]. Achieving these targets is essential for aligning with global emission reduction goals.

In Europe, the vast majority of buildings are characterized as energy inefficient. Data indicate that approximately 97% of the EU's building stock requires upgrades to achieve high energy efficiency standards. Currently, less than 3% of these buildings meet the highest energy performance ratings. This highlights the critical need for extensive renovations across the EU region to enhance energy efficiency and reduce energy consumption [4][5].

In terms of energy consumption, residential buildings account for a significant share of the EU's final energy use. Buildings represent approximately 40% of the total energy consumption in the EU. Specifically, households contribute about 25-27% to the final energy use, with space heating alone comprising roughly 63% of household energy consumption [6][7]. These statistics highlight the critical importance of improving energy efficiency in buildings to meet the EU's climate and energy objectives.

Initiatives such as the EU's Renovation Wave, which aims to double the annual rate of energy renovations by 2030, are essential for achieving these goals [2].

Recent advancements in forecast control methods for heating systems have shown promising results in optimizing energy use and improving occupant comfort by leveraging predictive algorithms and weather forecasts. Model Predictive Control (MPC) has continued to gain traction as a superior approach to managing heating systems.

Miezis et al. [8] presented a methodology, which allows the creation of a multivariate constraint model, incorporating key constraints like building thermal capacity and energy prices. Using weather forecasts, the predictive control optimizes resources and anticipates outdoor temperature changes. Real-time MPC modeling has reduced energy consumption and costs. Besides by integrating weather forecasts and electricity tariffs, MPC improves heat source scheduling and achieves financial savings.

Rasku et al. [9] demonstrated the effectiveness of the open-source Backbone energy system modeling framework for simplified model-predictive control (MPC) of buildings. Hourly rolling horizon optimizations were conducted to minimize heating and cooling electricity costs for a modern Finnish house and an apartment block with ground-to-water heat pumps from 2015 to 2022. Using hourly spot electricity market prices instead of constant price signals resulted in annual cost savings of 3.1–17.5%, consistent with existing literature. The optimization horizon length did not significantly affect results beyond 36 hours. The study confirms that simplified MPC can be effectively integrated into large-scale energy system modeling frameworks, providing rational and cost-saving outcomes.

Joe et al. [10] introduced a smart operation strategy using model predictive control (MPC) to optimize hydronic radiant floor systems in office buildings, with results from real implementation. The MPC approach used dynamic estimates of zone loads, temperatures, weather conditions, and HVAC system models to minimize energy use and costs while ensuring comfort. Data-driven building models were validated with real data, and the optimizer employed constraint linear/quadratic programming for a global minimum. The results showed 34% cost savings during cooling and 16% energy reduction during heating compared to baseline control.

Brown and Beausoleil-Morrison [11] reports on a 182-day implementation of a model predictive controller (MPC) for managing hydronic floor heating and cooling in a highly glazed test house in Ottawa, Canada. The MPC aimed to minimize energy use while keeping indoor temperatures within a set range, achieving success 71% of the time.

Pedersen et al. [12] investigates the impact of incorporating nonlinear dynamics of hydronic radiators in model predictive control (MPC) schemes for demand response (DR) in space heating. Results show that nonlinear thermal effects have minimal impact on DR performance compared to simpler linear models for convective heaters, with cost savings of around 5% for existing buildings and 18% for retrofitted buildings. These findings suggest that linear models are suitable for MPC in buildings with hydronic systems, and that a practical two-level control scheme could be effectively applied in real-world applications.

Prívara et al. [13] discusses the application of a model predictive controller (MPC) for temperature control in a real building, addressing limitations of conventional strategies like weather-compensated control, which often fail to leverage solar gain and can lead to underheating. The MPC integrates weather forecasts and a thermal model of the building to optimize energy consumption and maintain desired indoor temperatures regardless of external conditions. During one heating season, the controller was tested in a large university building, resulting in energy savings of 17–24% compared to the existing control system.

This short literature review demonstrated a significant amount of work on the use of model predictive control (MPC) in predictive control of heating systems. Numerous studies and implementations have focused on integrating MPC with installations involving heat pumps, highlighting its effectiveness and efficiency. However, there is a notable gap in the literature regarding the application of forecast control to traditional hydronic heating systems, indicating an area for further research and development. This paper describes a cost-effective, easy-to-install, and user-friendly system, alongside a simplified method for forecast control of heating systems in existing buildings with hydronic heating installations, which was developed by authors. The proposed method integrates the building's actual energy model and the installed heating system, (represented as an equivalent outdoor temperature), user behavior and user preference profiles, (expressed as an equivalent indoor temperature), and weather parameter forecasts.

2. Materials and Methods

The described forecast control method has been invented and described in a series of articles authored by Cholewa et al.[14][15][16][17], and the following article is an overview of the research presented in the mentioned literature.

The studies on forecast control of heating systems were conducted in multi-family residential buildings and public office buildings located in the Lublin province, south-eastern Poland. This region experiences a continental European climate characterized by very cold winters. The heating season comprises 3957 heating degree-days (HDD) and lasts 222 days annually. Prior to the initiation of this research in 2011, the building envelopes underwent energy renovations. Specifically, double-glazed windows with a U-value of 1.8 [W/m²K] were installed, and external walls were thermally insulated to achieve a U-value of 0.30 [W/m²K], aligning with the maximum allowable U-values for building elements under the Polish national energy code of that period.

All tested buildings are integrated into the city's central district heating network, with heat supplied through individual heating substations. The heating installations are traditional water-based systems featuring vertical risers connected to convection radiators, ensuring thermal comfort in the heated rooms.

The standard operating conditions include a supply water temperature of 80°C and a return water temperature of 60°C, with an indoor temperature setting maintained at 20°C.

All the surveyed buildings are equipped with weather-based controllers. This type of regulation of heating systems is achieved through qualitative control, which adjusts the supply medium temperature in response to variations in outdoor temperature, while maintaining a constant flow of the system medium. The weather regulator operates by measuring the outdoor temperature and calculating the necessary temperature for the medium supplied to the heating circuit, based on a predetermined heating curve.

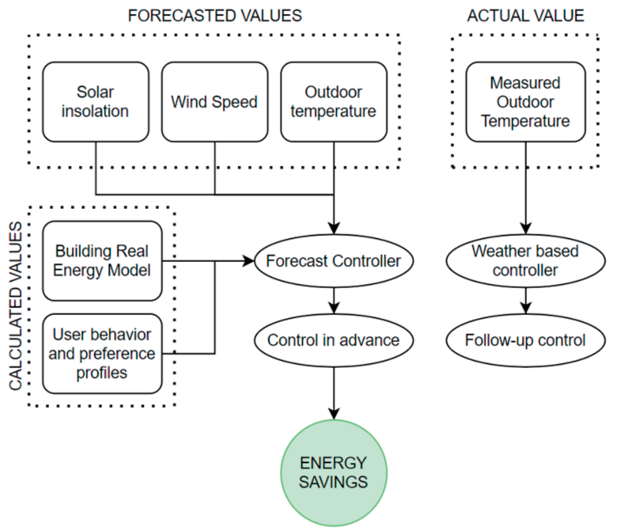

Fig. 1. Differences between the key characteristics of weather-based control and forecast-based control for heating systems.

The differences between the forecast control system and weather based control of heating system are presented in **Fig. 1**.

The process of implementing the forecast control in the building (**Fig.2**) comprises four primary stages, which involve:

1) setup of the proposed forecast control system in the building (refer to section 2.1);
2) constructing the energy model of the building (refer to section 2.2);
3) specifying the configurations for the forecast control systems (refer to section 2.3);
4) operating the proposed system in examples (refer to section 3).

2.1. Setup of Forecast System in Existing Buildings

To enable the operation of a forecast control system for heating installations in buildings, two options should be considered: installing a predictive module that collaborates with the existing weather controller, or mounting a forecast controller in place of the existing weather controller or as a new device in a building being put into use.

The installation of a forecast module in an existing building takes less than 2 hours and involves connecting the existing outdoor temperature sensor to the forecast module, and then connecting the forecast module to the existing weather-based controller.

For monitoring the heat delivered to the heating system, it is recommended to connect the forecast module to the existing heat meter or use a flow meter in the heating system circuit along with two temperature sensors. If there is no need for additional wiring, the entire installation process takes no more than 1 hour and does not require technical documentation of the building or heating installation.

However, it is worth noting that the proposed predictive control system is best suited for buildings with a single water heating system with convective radiators, supplied from risers or bottom-top from distributors. Conversely, in buildings where heat is delivered through heating-ventilation appliances or air conditioning units, the effectiveness of prediction may be limited due to the diversity of external and internal factors and their impact on heating systems.

For existing buildings, the forecast module is recommended due to its simplicity and cost-effectiveness, while the forecast controller is better suited for new constructions or comprehensive renovations.

Both options enable real-time energy modeling, facilitating informed decision-making regarding heating system optimization. They can easily interface with existing heat meters or flow meters, providing accurate data on heat consumption for space heating purposes. This integration typically takes about an hour, ensuring minimal disruption to building operations. Communication and data transfer are efficiently managed through Global System for Mobile Communications (GSM) technology, enabling remote management and adjustment of settings via a cloud-based IT system. This feature enhances the system's versatility and ease of use, allowing for seamless integration into existing building management processes.

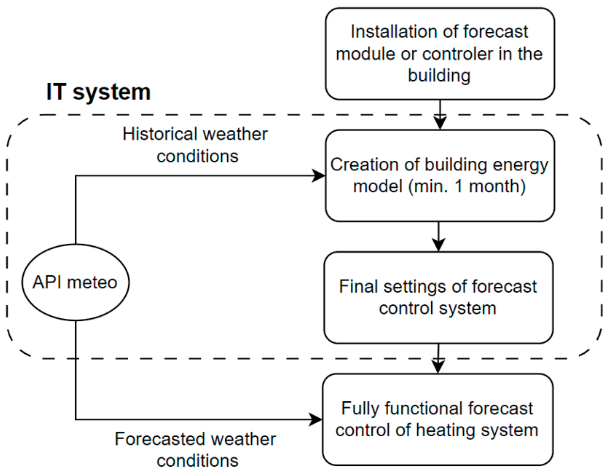

Fig. 2. The process of implementing the forecast control in the building

2.2. Creation of Building Energy Model

Immediately following the installation of the forecast control system (either version 1: the predictive module, or version 2: the predictive controller) and its connection to the central IT system, the automatic process of data collection begins.

This system records measurement data, including at least the outdoor temperature and the supply and return temperatures. The system archives key data for each building at high resolution (every 15 minutes), which is uncommon in similar heating monitoring systems that usually record data every 30 or 60 minutes. Additionally, these are real-time values sampled at 1-minute intervals, greatly enhancing the accuracy and value of the archived data.

After the control system is installed in the building, the heating system operates in weather regulation mode for at least one month (preferably an entire heating season), gathering the necessary data to build the building's energy model. This energy model also accounts for the actual efficiency of the existing heating system.

The data transmitted from each building can be used to create a reliable energy model, incorporating the actual efficiency of the heating system, in the form of an equivalent outdoor temperature (T_e^{eq}). This model adjusts the outdoor temperature based on wind speed (V_{wind}) and solar insolation (I_{nsol}).

Developing a building's energy model requires local meteorological data, including solar isolation and wind speed. Since not all buildings have on-site weather stations, historical data is retrieved from the meteo API integrated into forecast module, accessing data from the nearest meteorological station using the building's coordinates.

Within the IT system, users can adjust the hourly data range for a specific building to refine the outdoor temperature corrections for the energy model. During the data collection period, the heating system operates with a weather-based controller. Once the energy model is developed, the operating mode of the controller can be remotely adjusted through the IT system.

Universal computational algorithms have been developed to create the building energy model (building and heating system).

This model is expressed in terms of an equivalent outdoor temperature T_e^{eq} that accounts for the effects of wind speed and solar radiation (see Equation 1). This is crucial for forecasting the heating power demand and for efficiently controlling heat supply, which can lead to energy savings while maintaining thermal comfort for the occupants. Therefore, **Eq. (1)**, which defines the equivalent outdoor temperature T_e^{eq} for a given, will include adjustments for wind speed T_V^{rev} and solar insolation T_{insol}^{rev}.

$$T_e^{eq} = T_e - T_V^{rev} + T_{insol}^{rev} \quad [°C] \qquad (1)$$

The corrections for wind speed and solar insolation are derived from a dataset of suitably selected observations, using a regression equation that should exhibit a high coefficient of determination (R^2).

To calculate the corrections of outdoor temperature due to wind speed, an universal algorithm was developed to compute outdoor temperature corrections based on wind speed, aiming for a minimum coefficient of determination of 0.85 for each building. Initial parameter identification aimed to minimize confounding factors such as sunlight and users activity.

The relationship between heating power and outdoor temperature was assessed across wind speeds ranging from 1 [m/s] to over 10 [m/s], considering average and maximum hourly wind speeds during different daily periods. The highest coefficients of determination were observed during night time hours (23:00-4:00) for both maximum and average wind speeds, attributed to minimized external and internal factors. Consequently, the data from these night time periods were utilized for a sample to ensure precise corrections. Regression equations specific to each wind speed were preferred over using wind speed ranges, facilitating more accurate adjustments.

Using these regression equations, heating power was calculated as a function of external temperature (-20°C to +10°C). Logical data ranges were selected, demonstrating an increase in heating power with wind speed. The preliminary correction value of external temperature due to wind speed was determined to align with heating power values at different wind speeds. These dependencies necessitate individual determination for each building due to varied responses to wind speed.

To calculate the outdoor temperature corrections due to solar insolation, a universal computational algorithm was developed, crucial for accurately predicting heating energy consumption in buildings. This algorithm considers external air temperature, wind speed, and either sunlight or cloudiness as influential factors. Parameters were meticulously defined to minimize the influence of confounding variables, such as wind speed and user activities, and ascertain the most reliable parameter for analysis: sunlight or cloudiness. The relationship between heating power and external temperature was analyzed for various sunlight ranges and cloudiness levels, considering different wind speeds and time periods (6:00-18:00 and 10:00-14:00).

Data analysis revealed that reliable results were obtained for wind speeds below 3 [m/s], indicating a minimal impact of wind on heating power and highlighting the effect of solar radiation. Consequently, to determine external temperature corrections due to solar radiation, data from periods with wind speeds below 3 [m/s], specifically between 10:00-14:00 on weekdays or weekends, were considered.

While logical results were not obtained for cloudiness analyses, logical relationships were observed for sunlight under wind speeds below 3 [m/s]. Sunlight was identified as a more reliable parameter compared to cloudiness, given its higher coefficients of determination and the limitations associated with estimating cloudiness without instruments. The algorithm for determining external temperature corrections due to solar insolation mirrors that for wind speed, emphasizing the importance of considering specific time periods and wind speeds to accurately capture the impact of sunlight on heating power demand while minimizing the influence of other factors.

Regression equations were developed for each sunlight range and wind speeds below 3 [m/s] to calculate heating power based on external temperature. Preliminary external temperature corrections due to sunlight were computed, and an average correction for each sunlight range was determined, facilitating the creation of a scatter plot of outdoor temperature correction versus sunlight to further refine the algorithm.

This comprehensive approach enables precise adjustments for solar radiation effects on heating power demand, enhancing the accuracy of predictive heating energy consumption models for buildings.

Additional research efforts were aimed at determining the impact of user behaviors and preferences on the heat consumption within buildings/facilities. This endeavor sought to develop universal, intelligent computational algorithms for the purpose of determining and subsequently selecting (individually for each building) an appropriate profile of equivalent indoor temperature. This profile accounts for the user-related aspect in predicting heat consumption. To develop profiles of equivalent indoor temperature, a methodology was developed to determine the heat loss coefficient, H [kW/K], for each building empirically. Utilizing an equation along with historical data of real heat consumption during night time periods (23:00-4:00), the coefficient was calculated, considering variations in user behavior. This approach, while contrasted with deriving H from design documentation or energy audits, ensures an accurate reflection of the building's thermal dynamics. Computation of H for each day and hour throughout the heating season is advised, with an average calculated from night time hours during the peak heating season (January to March), accounting for users behavior.

The average heat loss coefficient should be updated following any building modernization to reflect alterations in design heat load and heating power requirements. Hourly values of equivalent indoor temperature are derived from the determined H, facilitating the estimation and consideration of user behavior and internal heat gains affecting heating power demand in predictive control. An hourly profile, crucial for predicting heating power demand, is developed, considering potential variations in user preferences and behaviors. Four profile cases were considered, each tailored to minimize discrepancies between predicted and actual heat consumption.

The selection of the appropriate profile is automated using computational algorithms integrated into the Information System (NSI) for predicting heat consumption, ensuring accurate predictions for the upcoming week.

The entire computational process for determining the building's energy model (including its heating system) as an equivalent outdoor temperature is carried out independently for each building within the framework of the Supervisory Information System (NSI). The scope of input data for building the model can be individually tailored for each building using the NSI. After one month (minimum 1 month, but a full heating season is recommended) from the installation of the control system in the building, the actual energy model of the building can be determined as an equivalent outdoor temperature. The entire computational process for one building takes up to 10 seconds, and the computation can be initiated manually by the user or automatically after prior scheduling.

2.3. Configuration of the Forecast Control System

The creation of the building's energy model necessitates local meteorological data, such as solar insolation and wind speed.

However, not all buildings have on-site weather stations. Consequently, historical data of this nature is acquired from the meteo API, integrated into forecast control system to retrieve pertinent data from the nearest available meteorological station based on the building's specific coordinates. Within the IT system, users can adjust the hourly data range for a particular building to develop corrections for outdoor temperature, which are then incorporated into the building's energy model.

During the data collection phase for building energy modeling, the heating system is controlled using a weather-based controller. The operational mode of the existing weather-based controller can be remotely modified via IT system only after generating the actual energy model of the building.

The weather-based control of the heating system operates with a delay, adjusting the heating medium supply temperature settings based on the current or recent outdoor temperature values. This control method does not consider factors such as wind speed, solar radiation, or user preferences. In contrast, the primary objective of the heating system forecast control is to proactively adjust heat supply based on forecasted changes in weather parameters and user behavior. This includes considering factors like thermal inertia and the heating system's response to weather conditions.

Before transitioning from weather-based to forecast control it is essential to verify and adjust forecast control settings for each building. Key considerations include correcting outdoor temperature for wind speed and solar insolation, particularly in response to forecasted increases in outdoor temperature. Wind correction involves adjusting heating medium supply temperature to counteract increased heating loads caused by lower ambient temperatures due to wind. Solar insolation correction anticipates higher outdoor temperatures due to increased solar gains. Furthermore, the forecast control process allows for setting suitable day and night setbacks for equivalent indoor temperature.

This accounts for occupant preferences, behavior, and heat gains associated with occupancy and activities. All settings and values can be customized for each building by using the IT system to optimize energy savings while ensuring users comfort.

3. Operating of the Proposed Forecast Control System

Once the forecast control settings are input, a crucial aspect is managing the transition from predicted heat consumption (Q_{pred}) to the outdoor temperature setpoint value (T_e^N). This transition is facilitated through the forecast module, where the predicted heat consumption (Q_{pred}) is calculated using **Equation (2)**, considering factors like equivalent indoor temperature T_i^{eq}, equivalent outdoor temperature T_e^{eq} and the average heat loss coefficient for the building (k_{mean}).

$$Q_{pred}=k_{mean} \cdot (T_i^{eq} - T_e^{eq}) \quad [\text{kW}] \qquad (2)$$

However, to effectively reduce heat consumption in existing buildings, preemptive action is essential to adjust to changing external and internal conditions and provide a lower heat power than the direct forecast value.

When computing Q_{pred}^{final}, it's advisable to determine $T_e^{eq\_final}$, considering adjustments made for forecast control settings. This includes not correcting outdoor temperature for wind speed if it is below 10 [m/s], factoring in previously forecasted solar insolation values from 2 hours prior for outdoor temperature correction due to solar insolation, and considering the forecasted outdoor temperature increase from 2 hours earlier.

$$T_e^N = (T_i + T_{idecrease_{day}} + T_{idecrease_{night}}) - \frac{Q_{pred}^{final}}{k_{mean}} \quad [°\text{C}] \qquad (3)$$

Equation (3) is utilized to determine the outdoor temperature setpoint (T_e^N) for the upcoming 6 hours, considering hourly intervals. This approach allows for the consideration of day ($T_{i\_decrease\_day}$) and night ($T_{i\_decrease\_night}$) setbacks in indoor temperature, leading to additional energy savings. $T_{i\_decrease\_day}$ is suggested for implementation in public buildings during weekends when the building is unoccupied. Conversely, $T_{i\_decrease\_night}$ is recommended for night time use in any building type, when occupants are absent (e.g., public buildings) or asleep (e.g., residential buildings). The reduction in indoor temperature should not exceed 5°C. It is important to note that this temperature setback does not imply that indoor temperatures will drop by 5°C. Instead, applying this indoor temperature decrease (via **Equation (3)**) will raise the T_e^N, consequently lowering the supply temperature to the heating system and resulting in expected energy savings. In most multifamily and public buildings, the design indoor temperature (T_i) is typically set at 20°C.

The estimated T_e^N values for the next 6 hours are relayed to the forecast module (or forecast controller) within the specified building. These values are factored into the heat supply control process for heating, considering the heating curve stored in the existing weather-based controller, if it is available.

This cycle repeats hourly, with new T_e^N values recalculated and transmitted for the subsequent 6 hours, replacing the previous ones. If the T_e^N value for a given hour surpasses the current outdoor temperature measurement, the forecast module or controller integrates the T_e^N value into the control process instead of the measured T_e value. Conversely, if the hourly T_e^N value is lower than the current measured outdoor temperature, the forecast module or controller disregards the T_e^N value and uses the measured T_e value in the control process. This ensures that the heating system does not operate with a higher heating medium temperature in forecast control mode compared to its operation in simple weather-based control mode.

The implementation of forecast control in while long-term on-site assessment showed that multi-family buildings results in energy savings ranging from 11.3% to 18.9%, with an average savings of 13.4%. In the case of public utility and office buildings, energy savings ranged from 8.3% to 13.7%, averaging 10.7%. There, research cleared a trend of increased savings in larger buildings. The observed higher percentage of energy savings in larger buildings is primarily due to their substantial size and the presence of larger heating systems, which exhibit greater thermal inertia. Furthermore, the reduction in the supply temperature of the heating medium, facilitated by forecast control, is anticipated to enhance energy savings.

4. Conclusions

Long-term field research and monitoring of actual buildings have yielded valuable data for evaluating the effectiveness of implementing a forecast control system in existing residential and public utility/office buildings. This innovative forecast control system incorporates predictions of outdoor and indoor conditions, allowing for significant energy savings. Analysis of real-world long-term research data indicates that compared to traditional weather-based controllers, the forecast control system can achieve average savings of 13.4% in residential and 10.7% in public buildings. The payback period for implementing forecast control systems in existing residential and public buildings is approximately 0.6 heating seasons, on average. This duration can be notably shorter for larger buildings with higher pre-installation heat usage.

The effectiveness of the forecast control system is particularly pronounced in the regions characterized by higher daily temperature variations and extended periods of solar radiation. As such, it is highly recommended for use in climatic zones with these features, especially during transitional periods between seasons.

Installation and integration of the forecast control system are straightforward, requiring less than 2 hours and compatible with most existing weather-based control systems in buildings with hydronic heating installations. Its simplicity and independence from building documentation make it a cost-effective and time-saving solution for both existing and new buildings.

The system's predictive capabilities account for changes in external weather parameters and internal user preferences, resulting in tangible energy savings and enhanced occupant engagement in energy-efficient building operation.

With online access to operational energy data, occupants and facility managers can actively participate in optimizing heating system performance.

In conclusion, the proposed forecast control system offers a viable alternative to traditional weather-based controllers, providing an easy-to-install, cost-effective solution for improving energy efficiency in buildings. Ongoing research will further refine its performance under various operational conditions, including different building types, occupancy patterns, and climate zones, paving the way for broader implementation in buildings worldwide and also verifying the potential applicability of the developed algorithm in cooling systems.

Integrating the proposed forecast control system into buildings with diverse heating systems, such as HVAC systems, presents several challenges. One key issue is compatibility with varying control protocols and operational characteristics of these systems. HVAC systems often employ complex controls that may not seamlessly align with our predictive algorithms. Developing adaptable interfaces or hybrid control strategies may be necessary to enable effective collaboration between our system and existing HVAC controls.

Additionally, each building has unique thermal dynamics and energy usage profiles, necessitating customization of control algorithms. This could involve calibration processes that add complexity to the initial implementation phase.

Broader geographical coverage introduces challenges related to climate variability. Our current study's results, based on specific climatic conditions, need validation across different environments. Future research will focus on conducting field tests in diverse climates to gather data on extreme temperatures, humidity levels, and solar gain patterns. This will allow us to refine our algorithms, ensuring their effectiveness and adaptability in various settings. By addressing these challenges, we aim to enhance the applicability and utility of our forecast control system in a global context.

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Digital Twin Models with ESG Methodology as a Tool for Transforming Solutions in the Transport-Energy Sector with Applications to Sustainable Tourism

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Abstract

The transport and energy sectors face significant challenges in achieving sustainability and efficiency. This paper explores the potential of digital twin (DT) models, coupled with Environmental, Social, and Governance (ESG) methodology, to transform solutions in these critical areas. Digital twins, i.e. virtual representations of physical systems, provide real-time data and insights for process optimization. ESG methodology, focusing on environmental impact, social responsibility, and good governance, guides decision-making towards sustainable practices. This paper investigates how digital twin models, integrated with ESG principles, can be used to: (i) optimize transportation networks: reduce traffic congestion, improve public transportation efficiency, and minimize fuel consumption, and (ii) enhance energy management, i.e. optimize energy production and distribution, integrate renewable energy sources, and reduce overall environmental footprint. Based on these insights, the combination of DT technology coupled with ESG methodologies is researched with respect to transformative opportunities for sustainable tourism, which can be applied across the transportation-energy sector by optimizing resource allocation, reducing emissions, and promoting social equity. The main finding is that digital twins, combined with ESG principles, offer a promising way to increase the tourism sector's sustainability by optimizing transportation and energy use, but successfully adopting these solutions may require changes in traveler behavior and careful consideration of many ethical and practical challenges.

Keywords: *Digital Twins; ESG Methodologies; Transport and Energy Sectors, Sustainable Tourism.*

1. Introduction

The transport and energy sectors are fundamental to modern society, but their reliance on traditional fuels and infrastructure creates significant challenges [1]. Environmental concerns, like greenhouse gas emissions and air pollution, necessitate a shift towards sustainable practices [2]. The transition towards decarbonized energy systems will generate disparate impacts across socio-economic groups, necessitating comprehensive analysis of potential inequities and the development of targeted policies to ensure an equitable energy transition [3]. Hence, ensuring equitable access to transportation and energy resources requires socially responsible solutions [4].

Digital technologies offer promising avenues for addressing these challenges. Digital twin (DT) models, virtual replicas of physical systems, are revolutionizing various industries by providing real-time data and insights for optimization [5]. In the transport sector, DTs can be used to monitor traffic flow, optimize public transportation schedules, and predict maintenance needs [6]. Similarly, within the energy sector, DTs can be employed to improve energy production and distribution efficiency, integrate renewable energy sources, and manage grid stability [7].

To ensure that these advancements contribute to a sustainable future, it is crucial to integrate environmental, social, and governance (ESG) considerations into decision-making processes. ESG is a framework used to evaluate a company's performance and impact beyond just financial measures, balancing its impact on the environment, treatment of its employees, customers, suppliers, and the communities where it operates, and its leadership, stakeholders, and overall transparency and ethical behavior [8]. ESG methodology emphasizes responsible practices across these three interconnected domains [9]. By incorporating ESG principles, DT models can be harnessed to develop solutions that not only optimize efficiency but also minimize environmental impact, promote social equity, and prioritize responsible governance [10].

Significant research and development efforts are focused on advancing digital twin (DT) technologies. These efforts include improving sensor technologies for real-time data collection, enhancing simulation and modeling capabilities, and developing advanced analytics for extracting insights from complex DT models [11]. The digital twin model integrates the following sub-domains into a functional framework: physical entities, virtual models, services, digital twin data, and mutual connections (interrelationships), as shown in Fig. 1. Furthermore, work is underway to address cybersecurity and data privacy issues surrounding DT implementation [12]. Additionally, integration with technologies such as artificial intelligence (AI), machine learning (ML), and cloud computing is continuously evolving [13].

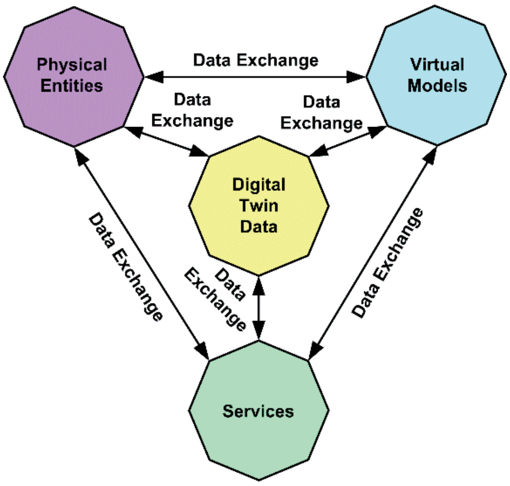


Fig. 1. The five-dimensional digital twin model representation [11].

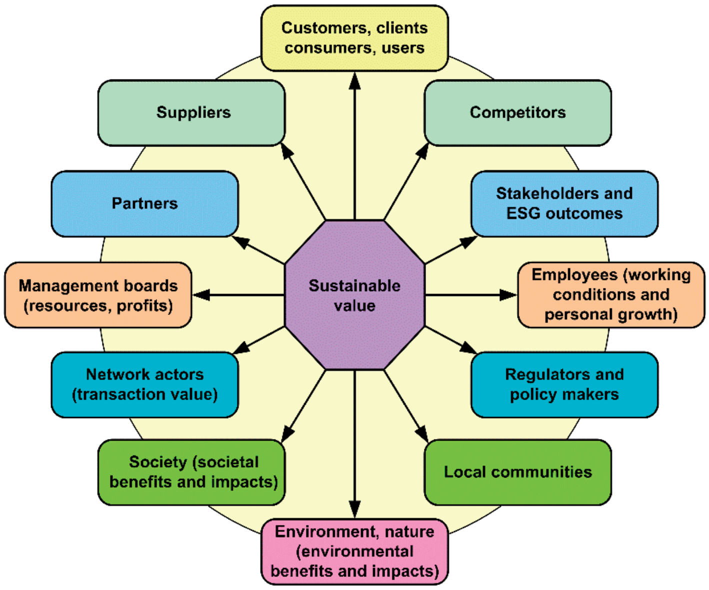


Fig. 2. Stakeholder groups and sustainable value creation process [15].

Simultaneously, there is increasing emphasis on aligning technological advancements with Environmental, Social, and Governance (ESG) principles, and reducing the dependence on fossil fuels [14]. Researchers are exploring ways to utilize DT models to measure and improve ESG performance. This includes investigating carbon footprint reduction strategies, optimizing responsible resource use, and ensuring social equity in the development and deployment of these technologies [15]. Reference [16] underscores the importance of recognizing distinct stakeholder groups and examining how sustainable value is generated across different levels, encompassing diverse forms. This multifaceted analysis is illustrated in Fig. 2, which outlines both the stakeholder groups themselves and the corresponding mechanisms for creating sustainable value tailored to each group. In that respect, the triple bottom line concept has been introduced to measure the enterprises' adherence to sustainability principles [17]. Additionally, efforts are underway to establish standards and governance frameworks for transparent and accountable ESG reporting, as indicated in [18].

This research explores the transformative potential of DT models integrated with ESG methodology for the transport and energy sectors. We investigate how this approach can be leveraged to optimize transportation networks, enhance energy management, and ultimately contribute to a more sustainable future. In the following sections, the current state of the transport and energy sectors are explored, highlighting the need for sustainable solutions. The potential of DT models and ESG methodology is examined, followed by a detailed examination of how their integration can transform these critical sectors.

2. Transforming Transport with Digital Twin-ESG Solutions

Digital twin (DT) models integrated with ESG principles offer a powerful approach for optimizing and greening the transport sector. This chapter explores some recent case studies showcasing how this combined approach is driving positive change into the transportation sector.

2.1. Road Transport

A study conducted by the University of New South Wales [19] examines how Siemens MindSphere, a cloud-based DT platform, is being used to optimize public transportation systems in a major European city. The DT model integrates real-time data from traffic sensors, buses, and trams. This data is used to monitor traffic flow, predict congestion, and optimize route planning. Additionally, the model considers social equity factors by analyzing accessibility for underserved communities. The study also reports a significant reduction in traffic congestion and emissions, along with improved service reliability and accessibility. In reference [20], a flexible mobility DT framework is designed, incorporating AI, cloud-edge-device technologies, and digital replicas of human drivers, vehicles, and traffic dynamics. This framework, implemented within Amazon Web Services, offers functionalities like data storage, modeling, learning, simulation, and prediction. A case study of a personalized adaptive cruise control system showcases the framework's ability to integrate driver behavior modeling, cloud-based driver assistance systems, and traffic flow management. The research presented in [21] proposes a DT for Badalona's (Spain) public transport system to gain deep insights into bus dynamics. Using a genetic algorithm with real-world data, the research has yielded a system that accurately replicates bus schedules and traffic flow, while also adapting to unforeseen situations thus accommodating the passenger comfort and satisfaction.

A study presented in [22] proposes a multi-level cooperative driving framework for urban arterials, accommodating a mix of connected vehicles, connected automated vehicles, and regular vehicles. The model is aimed to optimize the traffic flow to minimize fuel and energy con-

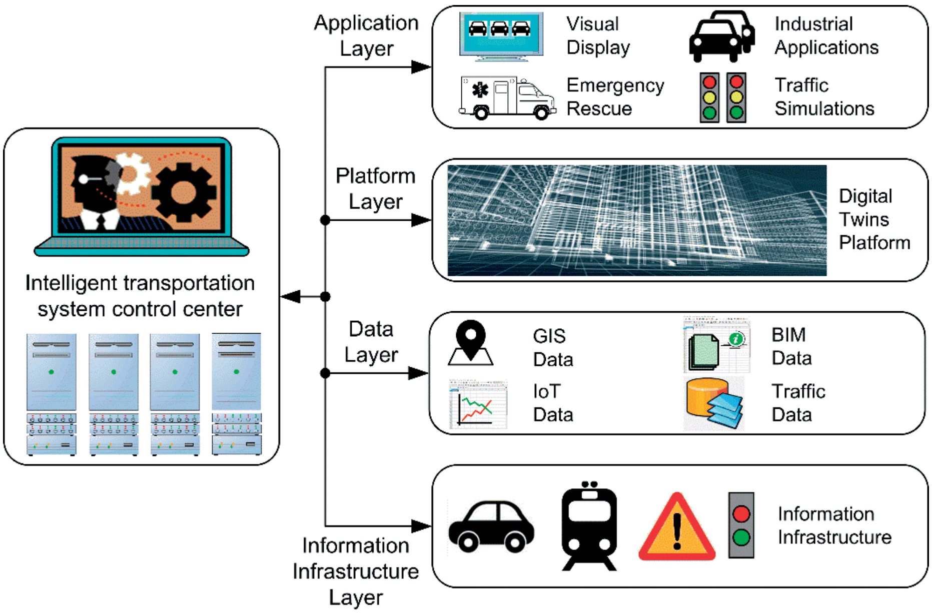


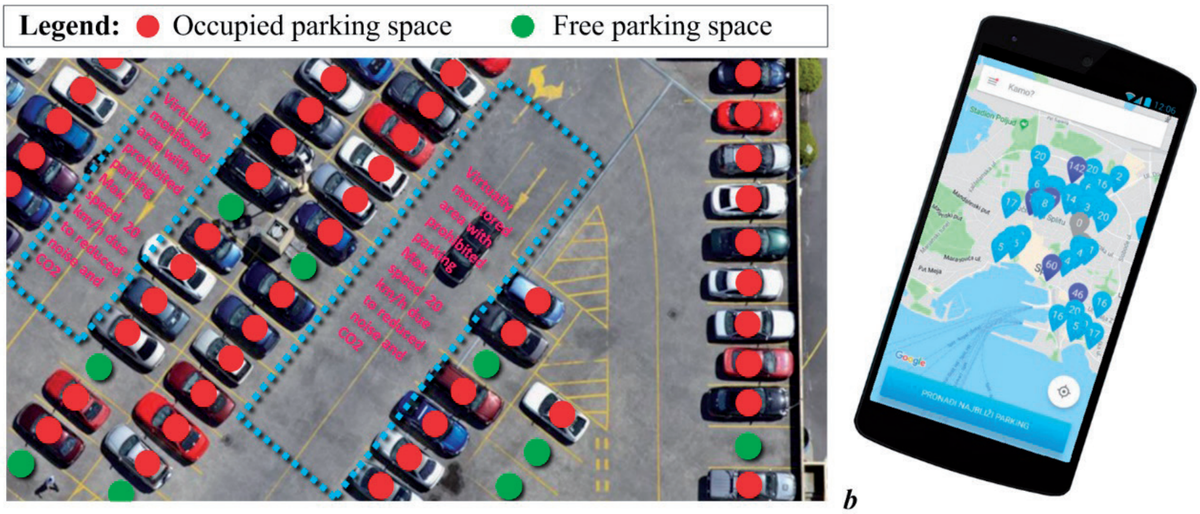
Fig. 3. Digital Twin-based smart transportation platform architecture from [25].

sumption by using centralized control, where communication infrastructure optimizes signal timing and provides general guidance, with distributed control for individual vehicle trajectories. Simulations on a real-world arterial show significant reductions in delays and fuel consumption across various traffic compositions and automated vehicle percentages. Sensitivity analysis confirms the benefits are robust to traffic volume fluctuations. Another innovative approach to smart mobility challenges using digital twins has been proposed in [23]. Leveraging digital replicas of urban environments and utilization of the so-called "meta-cities" architecture for smart mobility, the presented study aims to optimize traffic flow, reduce environmental impact, and improve emergency response through real-time monitoring and analysis.

Only the interaction of different aspects of sustainability makes the transport system of a tourist city future-proof and ensures long-term success and growth. Sustainability not only includes environmental issues, but also considers social aspects and key aspects of good and transparent corporate governance. For this reason, it is necessary to statistically collect traffic information and measure its parameters (e.g. by using an IoT network of distributed sensors), with the goal of successfully implementing corrections and making transparent and measurable decisions for the successful implementation of ESG sustainability parameters, especially for tourist locations that require measuring the traffic load in real time.

The city of Graz, Austria, is trialing a smart traffic monitoring platform to improve cycling infrastructure and support its climate goals. This GDPR-compliant system uses AI-powered video analysis to accurately distinguish between cars, cyclists, scooters, and other road users within the traffic model, thus overcoming limitations of traditional sensor-based solutions. The system transmits data via mobile networks for easy installation on the existing infrastructure. Graz aims to use the collected data, including traffic infringement information, to enhance road safety and potentially expand the system city-wide. The project supports not only green initiatives but also the development of autonomous vehicles (AVs) and the EU's Vision Zero goal by providing detailed traffic data [24]. The study presented in [25] analyzes how DTs can be applied to intelligent transportation systems and model traveler behavior under unexpected events, with the smart transportation platform DT architecture shown in Fig. 3. It integrates multi-source spatial and IoT data to construct virtual transportation scenes using 3D modeling and simulation tools. This study proposes an Internet of Vehicles (IoV) system that integrates DTs with blockchain technology to address data redundancy and vehicle data sharing issues. The study concludes that enhancing DT resilience directly translates to a more adaptable transportation system. A network traffic prediction algorithm for Vehicular Ad-Hoc Networks with fluctuating traffic flows is proposed in [26] to accommodate for the vast amount of data generated by Intelligent Transportation Systems (ITS). The algorithm combines Deep Learning methodologies for traffic prediction with Generative Adversarial Networks (GAN) to improve the traffic prediction accuracy, which is crucial for network management and security.

The challenge of the availability of tourist destinations is mainly related to the road transport infrastructure, which must meet the large and changing seasonal traffic demands. There is a great challenge of managing parking facilities in old urban centers that have a large increase in tourist arrivals, and on the other hand, increased demands on environmental sustainability. Due to new trends in tourism with highly mobile tourist demands, it can be surmised that a more accessible tourist destination will likely have better utilization of tourist capacities. For these reasons, tourist cities are looking for transport solutions that are increasingly complex due to the impossibility of expanding the old city infrastructure. Such new and sustainable traffic solutions are being developed in the direction of digitization and the introduction of artificial intelligence, especially in parking systems.



a *b*

Fig. 4. The concept of digital monitoring of available parking capacities in real time with features of a smart directional system to increase the sustainability of urban traffic (a) and the user graphical interface (b) showing parking locations in the Split metropolitan area.

The city of Split is one of the first cities in Croatia to introduce a comprehensive digitization of the transport system due to overloading during the tourist season. Parking was defined as one of the primary problems, so the implementation of the digitalization of parking capacities was initiated recently, according to the concept of monitoring the occupancy of the parking infrastructure, as illustrated in Fig. 3. The digitalization of the parking infrastructure has been carried out by means of advanced sensors such as high-definition (HD) video and forward-looking infrared (FLIR) cameras whose data is collected in real time and processed to determine the currently available city-wide parking capacities, and those at the individual parking lots (see Fig. 3a). The parking space data within the centralized database will then be made available to subscribers within a mobile (smartphone) app, as illustrated in Fig. 3b. For more information about the digitalization project in question, the reader is referred to [27].

Traffic in cities is one of the greatest generators of CO2 emissions and noise and searching for a free parking space generates up to 30% increase in traffic in urban areas. There are significant user traffic challenges such as: the fastest way from the point of movement to the point of long-term stopping, the nearest parking lot, the nearest electric charging station. By introducing innovative digital technologies, such as ITS (Intelligent Transport Systems) and a different organization of traffic, fuel consumption and CO_2 emissions can be reduced, drivers can be dynamically directed to available parking spaces and can thus avoid congestion and traffic jams, which could potentially reduce or solve traffic issues in today's cities, especially in tourist areas that are subject to seasonal traffic variations.

Study presented in [28] highlights the importance of social equity in the transition to electric vehicles (EVs). They analyze the availability and affordability of EVs that are cornerstone for greener road transport, and advocate for solutions that optimize the placement of EV charging stations, ensuring accessibility for all communities, including those in underserved areas. In that sense, future DT models could assist in analyzing the key factors like population density, travel patterns, and existing infrastructure to identify optimal locations for charging stations, promoting social equity, and encouraging wider EV adoption. This, in turn, would contribute to a cleaner transportation sector and would reduce greenhouse gas emissions.

2.2. Rail transport and autonomous virtual-line transport

Digital twins (DTs) are gaining traction in various sectors, offering benefits for product quality, process optimization, and resilience enhancement. In railways, DTs coupled with artificial intelligence (AI) show much promise for predictive maintenance, streamlining operations and reducing unexpected failures [29]. The research presented in [30] presents a new conceptual framework, RailTwin, or a railway Digital Twin (DT) that combines real-time data (insight), future predictions (foresight), and combined analysis (oversight) to enable automation and actions. This framework leverages various AI techniques like Deep Learning and Reinforcement Learning to achieve these functionalities. Research by the French National Railway Company (SNCF Réseau) [31] details their implementation of a DT model for railway infrastructure management. The model incorporates data from sensors embedded in tracks, switches, and overhead lines. This data is used to predict maintenance needs, optimize resource allocation, and minimize disruptions. The DT model also considers environmental factors by identifying energy-efficient routes and optimizing train schedules to reduce emissions. The SNCF Réseau study reports increased efficiency in maintenance activities, improved safety outcomes, and a reduction in the environmental footprint of their operations.

A study presented in [32] highlights how weather conditions, like wind and humidity, can affect train safety and energy consumption. By analyzing these factors through

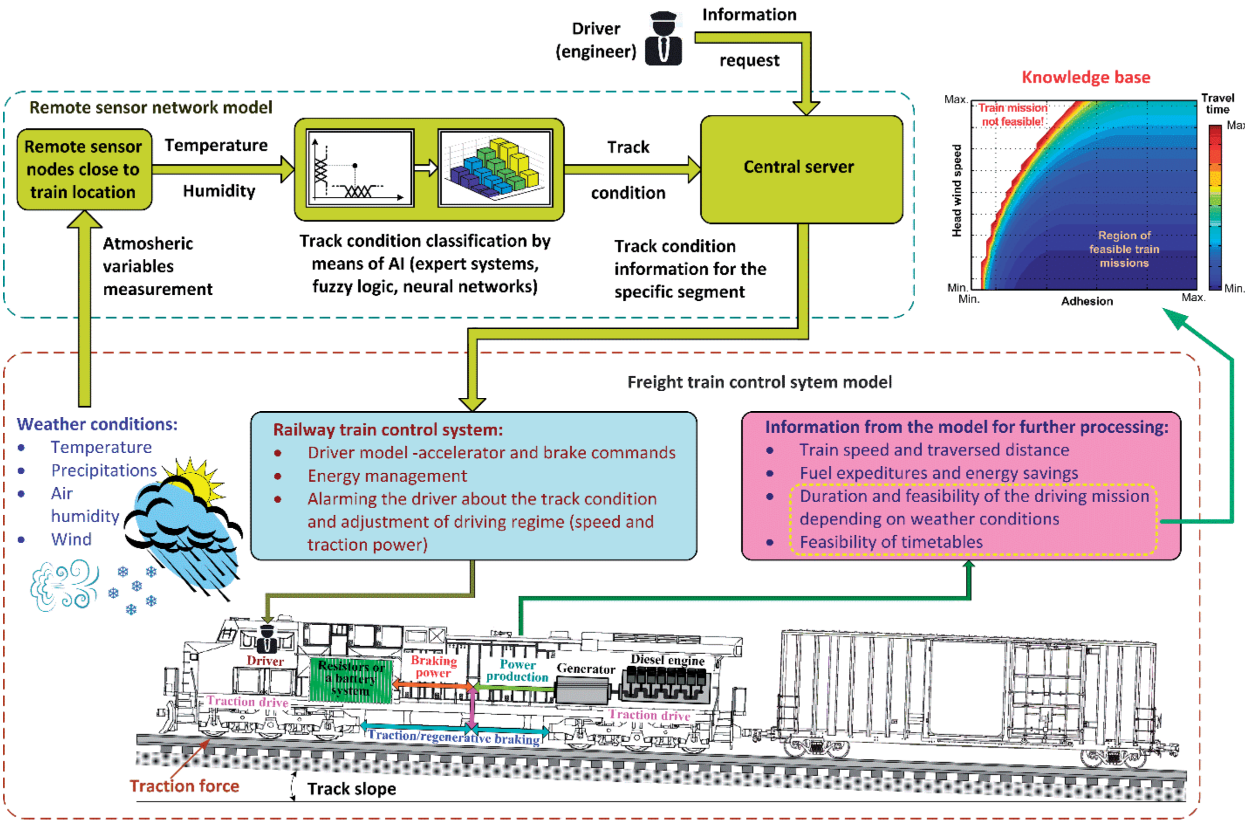


Fig. 5. Principal representation of train supervision system with information flow [32].

utilization of remote sensor networks, the study proposes a digital twin system equipped with AI features to predict challenging track conditions and adjust train driving missions and schedules accordingly (see Fig. 5). The study concludes that the presented approach could improve safety, optimize fuel usage, and contribute to a greener transportation sector through optimization of energy consumption with respect to micro-location weather conditions. Another example of utilization of AI for improved traffic safety can be found in [33] wherein a fuzzy logic algorithm is proposed to manage traffic during partial closures on a dual rail track, which is a common problem in railways and autonomous virtual-line transport (Fig. 6). The algorithm uses real-time queue data (from narrowband IoT sensors) to schedule the traffic flows. Compared to conventional methods, this approach has been shown to effectively reduce vehicle congestion under irregular traffic conditions (see Fig. 6).

Smart railway systems, integrating 5G and AI, pose challenges for wireless network management. Wireless Digital Twins (DTs) offer solutions for the entire lifecycle of these networks, as indicated in [34], with key technologies for railway-oriented DTs including characterizing material properties, reconstructing 3D environments, AI-powered analysis, and deterministic channel modeling methods for radio signal propagation simulation. The DT-based planning tool in question has been demonstrated to have the industrial value and has been adopted by the China Railway Engineering Design and Consulting Group to implement different advanced functionalities. Research conducted in [35] presents an augmented digital twin for railways, designed to enhance safety and efficiency in train operations by incorporating real-time derailment risk assessment. The digital twin combines a surrogate model, developed through extensive multibody dynamics simulations, with machine learning techniques to predict derailment risk based on factors like coupler force, speed, and track curvature. Successful implementation in a heavy haul case study demonstrates the augmented twin's potential to not only mitigate derailment risk but also support future advancements in reducing rail damage. More about next generation railway systems can be found in [36].

2.3. Other modes of transport

Digital Twins (DTs) are crucial for industries facing disruption from factors like rising costs and decarbonization mandates, and the whole maritime sector can significantly benefit from DT applications throughout the product lifecycle to tackle these challenges [37]. Modern seaport information systems leverage cutting-edge technology to analyze real-time data and are adopting Digital Twins as a key driver of Industry 4.0 integration. To that end, reference [38] paper examines the Digital Twin applications in global seaports, exploring implementation strategies, decision support, and challenges.

A collaboration between Maersk, a global shipping giant, and IBM showcases the potential of DT-ESG solutions in the logistics sector [39]. The project utilizes a DT model to track and optimize container shipments across the entire supply chain. The model integrates real-time data on

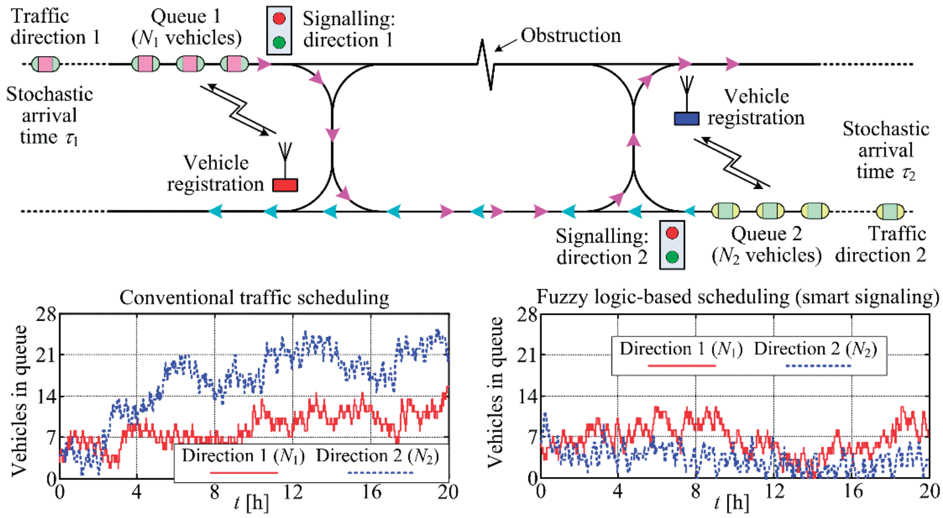


Fig. 6. Bidirectional autonomous virtual-line transport network segment under obstruction with signaling system and comparison of conventional and smart scheduling approach from [33].

location, fuel consumption, and emissions. By optimizing routes and logistics strategies, the project aims to reduce fuel consumption, minimize emissions, and improve overall supply chain efficiency. This case study demonstrates how DT-ESG solutions can contribute to a more sustainable maritime transport sector. To that end, reference [40] aims to improve efficiency and environmental compliance in maritime operations by using Deep Learning techniques on real-world data. A good survey of DT technologies and applications to future ports can be found in [41], along with some examples on how DT can contribute to energy efficiency and sustainability efforts by optimizing the use of port resources, facilities, and operations. The aerospace sector produces vast amounts of data that, with advancements in technology, can optimize the industry's processes. To achieve this, advanced system architectures and data models are needed to manage and integrate these diverse data sources. The study presented in [42] introduces an Airport Digital Twin concept, featuring a comprehensive data model used to streamline flight turnaround events. DT architecture in question has been validated at Aberdeen International Airport, Scotland, with the aim of reducing flight delays. On the other hand, airport ground delays can also significantly disrupt air traffic networks, so efficient ground handling is crucial to minimize delays and cascading effects. To this end, the study conducted in [43] presents a digital twin with agent-based modeling for Amsterdam Schiphol Airport's Pier H. It simulates ground handling activities and evaluates on-time departures under various scenarios, while also incorporating priority-based service rules, intelligent ground equipment to optimize service sequencing and resource allocation, along with an optimization model considers resource constraints and delays to achieve a cost-effective balance between airport demand and capacity. Results show that such strategies effectively reduce delays compared to the more traditional "first-in, first-out" (FIFO) approaches. A specialized DT platform has been proposed in [44] to conceptualize Urban Air Mobility (UAM) with unmanned aerial vehicles (UAVs) as a possible future transport solution, with the main obstacle currently being the integration of UAM into existing ground and air traffic systems, which requires a digital twin framework for network design and management. This particular DT concept has been applied to the airspace of Bologna, Italy, and has been demonstrated to prioritize safe routes and optimize connections between origin and destination points within the DT simulation environment.

Airports are actively working to reduce their environmental impact through initiatives like Airport Carbon Accreditation and collaborative management, whereas many terminals are pursuing Green Building Rating Standards (GBRS) certification [55]. However, existing standards don't fully address all environmental aspects of airport operations. Therefore, the research presented in [45] explores integrating GBRS with a more holistic approach, highlighting potential challenges. The proposed holistic scheme could improve environmental management, coordinate partner efforts, address construction and operational impacts, and enhance overall accountability. An example of such a holistic approach to airline transport greening can be found in [46] wherein OLGA, a Horizon 2020 project, drives the aviation sector towards sustainability with its innovative solutions. Addressing environmental concerns like carbon-dioxide emissions, biodiversity loss, air quality, and waste management, OLGA optimizes energy efficiency holistically across airports and the aviation value chain.

A study presented in [47] explores factors influencing consumers' willingness to pay for sustainable practices at airports (e.g., biofuels, green construction) and their intention to mitigate climate change. A survey of 722 participants in the US examined how factors such as environmental concern and perceived value of sustainability impact these behaviors. The study found that positive response towards climate action, perceived value of sustainability, and personal beliefs about climate change all significantly influence willingness to pay for eco-friendly airports, which in turn translates to a greater willingness to take affirmative action. A rather comprehensive literature review on impact assessment literature for green airports can be found in [48].

3. Powering a Greener Future with Digital Twin-ESG Solutions in Energy Sector

The energy sector, especially when considering the Smart Grid (SG) paradigm presents another critical area where DT-ESG solutions can revolutionize how we generate, manage, and utilize energy resources. While there's no single definition, a smart grid (SG) generally combines technologies to connect and optimize the actions of all users within the electricity network. This includes generators, consumers, and so-called "prosumers", with the ultimate goal of SG to maintain a continuous, efficient, economic, and sustainable energy balance [36]. Figure 7. illustrates the variety of hardware, software, and communications systems involved in an SG. The Smart Grid Architecture Model (SGAM) provides a framework for understanding complex smart grid systems, as illustrated in Fig. 8. It consists of five layers (business, function, information, communication, and component) that facilitate information flow between domains and hierarchical zones of the energy system. Reliable information and communication technology resources are essential for timely coordination between these layers, which means that designing efficient energy systems involves complex decision-making. An Interactive Digital Twin (InDiT) is introduced in [49], as a tool that assists decision-makers in exploring design options, which translates user needs and preferences into an optimization model, considering factors like uncertainty and multi-criteria analysis.

With the rise of interconnected energy systems in smart cities, managing these networks effectively is crucial from the standpoint of reliability. The research presented in [50] proposes an energy management tool that utilizes advanced control and machine learning to optimize energy use across a city district, coordinating various energy sources while accounting for user-defined goals and high-level system constraints. The particular open-source framework allows for adaptation across different energy sectors, as demonstrated in case studies of integrating heating systems and electric vehicle charging stations in London. The study has indicated that such an approach empowers local governments to manage energy assets collaboratively and achieve environmental, economic, and resilience objectives, thus aligning well with ESG criteria.

The growing complexity of power systems with distributed energy resources (DERs) demands efficient data management for reliable operation, with Digital twins (DTs) offering a promising solution. To this end, the study presented in [51] proposes a methodology for modeling energy cyber-physical systems (ECPSs) using two DT types to cover for high-bandwidth (high response speed) and low-bandwidth (low response speed) events, while also supporting centralized decision-making. The concept has been validated using Amazon Web Services (AWS) as a cloud platform, demonstrating real-time implementation with high accuracy. In addition, digital twins (DTs) are revolutionizing modern industries by creating real-time digital replicas of physical systems, while the growth of the Internet of Things (IoT) in power grids provides the data needed for DT implementation, as proposed in [52]. This particular study proposes DT applications across

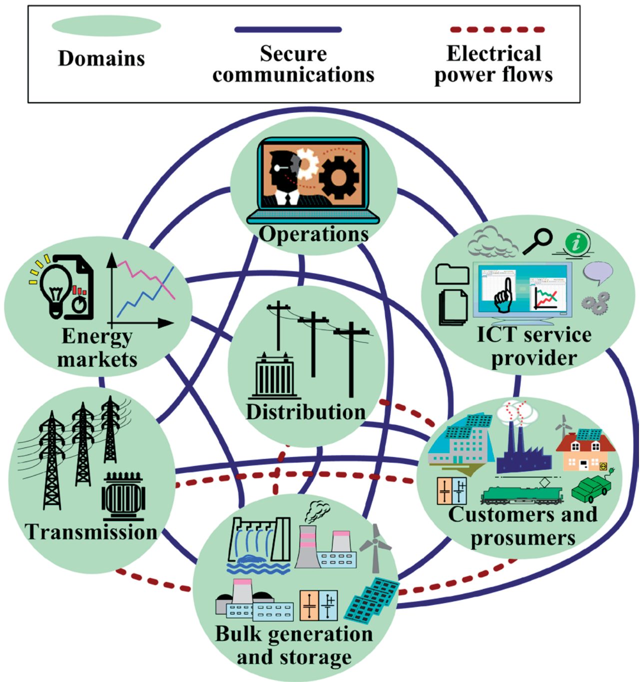


Fig. 7. Conceptual model of Smart Grid [36].

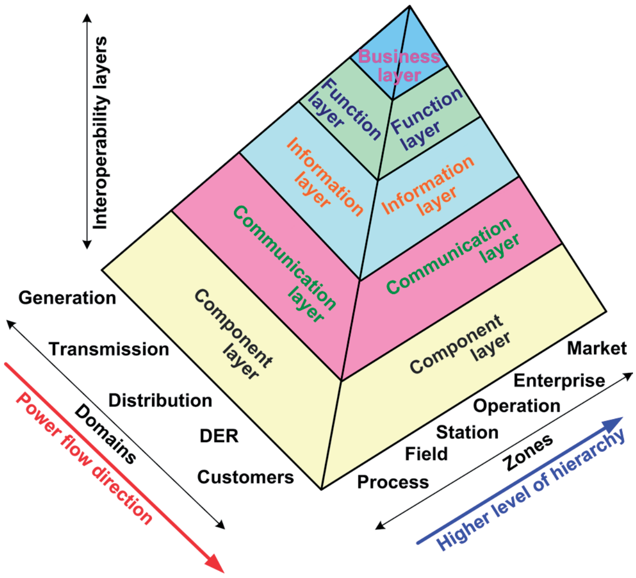


Fig. 8. Conceptual representation of smart grid architecture model (SGAM) [36].

various power system domains within smart cities, including transportation systems, smart grids, and microgrids, with real-time data analysis from DTs being able to address challenges like traffic management in transportation and remote data transfer in power grids. Security considerations for Machine Learning (ML)-based DTs are also discussed and a comprehensive guide for developing and deploying DTs for diverse power system applications has been presented as well.

Within the future smart energy systems, complex power plants demand robust DT architectures for optimized reliability, availability, and cost-effectiveness, as proposed in [53], wherein a comprehensive DT architecture has been developed for power plants, adaptable to similar engineering systems. The architecture in question integrates physics-based models, sensor data analysis, localized simulations, and a digital thread, fulfilling established DT requirements. The study has demonstrated its effectiveness for the case of anomaly detection for utility gas turbines in an operational power plant, thus also showing potential in improving the overall energy production resilience.

A review presented in [54] explores how Digital Twins (DTs) can be applied to Smart Energy Systems (SES) in the age of Industry 4.0. It investigates how DTs can address challenges in energy service provision and contribute to a more agile and intelligent energy sector (Energy 4.0). The review has included: (i) a description of the current DT applications in SES, (ii) identification of key DT applications, challenges, and implementation factors for Energy 4.0 management, and (iii) description of various approaches for deploying DTs within SES, thus providing a managerial guideline for practitioners considering future DT adoption.

Digitalizing the process and energy sectors with Energy Digital Twins (EDTs) promises significant advancements in energy management, optimization, maintenance, design, and renewable integration, as outlined in the review paper [55]. This review proposes a multi-dimensional EDT classification framework, outlining lifecycle applications, and suggesting how EDTs can reduce the environmental footprint of industrial sites and local areas, along with listing key challenges for future EDT adoption. The study presented in [56] explores using digital twins with 3D data, IoT, AI, and machine learning for intelligent energy management in a residential district. The case study focuses on Rinascimento III in Rome, a self-renewable energy-powered complex. It evaluates energy efficiency interventions using dynamic analysis algorithms to optimize energy use while maintaining resident comfort, with the goal of increasing self-produced renewable energy and achieving near-zero energy building standards, thus aligning well with the ESG criteria for future smart cities.

An example of challenges faced by future city designers is prioritizing building upgrades for energy reduction. While traditional benchmarking helps identify good and bad performers, it lacks details for actionable plans. To this end, the study presented in [57] proposes using smart meter data to create daily energy benchmarks for different building use periods. Unlike annual benchmarks, these segmented metrics reveal variations in efficiency throughout the day, week, or month, thus allowing for more targeted efficiency strategies and preparing for digital twin platforms that manage energy across entire building portfolios in near-real-time. A conceptual model for a Smart City Digital Twin (SCDT) specifically focused on disaster management is presented in [58], integrating sensors and simulations across various city systems that may be crucial for community management in disaster situations.

In conclusion, smart cities are seen as a solution to sustainability challenges, but face development hurdles, wherein Digital Twin Cities (DTCs) can be regarded as a transformative approach, with DTCs leveraging technologies such as IoT, AI, and blockchain to create digital replicas of cities, enabling better urban governance [59].

4. A Case for Sustainable Tourism using Digital Twins and ESG Methodologies

The global challenge of sustainable development requires a multi-dimensional approach, considering many aspects such as culture, structure, technology, and stakeholder collaboration. A key strategy is systems renewal, which involves prioritizing human needs and aiming for significant improvements in eco-efficiency. This requires strategic innovation and transdisciplinary collaboration to achieve viable results, especially when the transport-energy sector is considered due to its significant environmental impact [60]. This chapter will provide an overview of current efforts in sustainable development for the case of the tourism sector, which is highly dependent on both the transport and energy sector, with emphasis on digitalization, digital twins, and adherence to ESG methodologies.

Tourism's growth, especially in developing countries, has led to increased energy consumption, primarily from air travel, which has significant environmental consequences, necessitating the integration of energy use into sustainable tourism discussions [61]. The hotel industry, a major energy consumer within the tourism sector, often wastes energy due to a focus on comfort and competition. According to [62], there is a significant opportunity for hotels to implement renewable energy technologies and improve energy efficiency. Tourism transportation's impact on climate change also represents a crucial concern. Namely, a business-as-usual scenario will lead to undesirable consequences, making climate mitigation goals unattainable. Therefore, it is essential to consider long-term, macro-scale scenarios to understand both desirable and undesirable elements for the future of tourism transportation [63]. Statistical analysis has revealed a positive correlation between environmental indicators and tourism activity [64], with transportation used by tourists, especially road and air travel, having a negative impact on the environment. Promoting natural parks and encouraging more sustainable transportation methods can help balance these effects.

Sustainable tourism should not only consider local activities but also address the environmental impact of travel, especially in developed countries [65]. Therefore, reducing reliance on cars and planes is essential, posing a challenge for future tourism development. To achieve sustainable tourism transportation, behavioral change is necessary, as technology alone may not be enough to mitigate climate change. Models incorporating psychological economics and product diffusion theories can help evaluate the long-term policy impacts and promote sustainable travel choices [66]. Sustainable transportation also requires understanding of the psychology of travelers [67], because individual mobility decisions are influenced by both internal factors (attitudes, preferences) and external factors (price, speed). Therefore, transport policies can be more effective by considering these psychological aspects. In that sense personalized systems can incentivize sustainable travel behavior by learning individual preferences and promoting alternatives. According to [68], using control theory approaches in combination with domain knowledge in developing new travel planning strategies, these novel systems can effectively influence choices like departure times, potentially reducing overall travel time and promoting sustainability.

Digital twin (DT) technology, emerging from AI and IoT, has the potential to improve smart and sustainable tourism by predicting system responses. However, challenges such as regulatory compliance, stakeholder communication, and data security need to be addressed, so a documentation framework applying big data governance to the digital system is proposed in [69] to ensure accountability and trust in these novel concepts. Digital twins can also be used to enhance management, virtualize testing and maintenance, and maximize efficiency gains in smart cities by focusing on practical applications like GIS and BIM fusions, which can aid urban designers in placemaking and consultation [70]. Digital twins of the urban ecosystem are also a popular and mainstream trend in the digital development of territories worldwide [71], with their use within the urban ecosystem allowing the municipal authorities to obtain effective levers of management, and to enhance the quality of life within the city. Digital twins can also utilize Big Data to create virtual representations of regions and analyze visitor activity thus enabling smart and sustainable tourism [72]. However, this also requires addressing regulatory compliance and stakeholder communication. It also requires resolving issues of Big Data governance, whose framework comprises policies, guidelines, and procedures to effectively manage large volumes of structured and unstructured data, enabling efficient data discovery, collection, processing, analysis, and storage (Fig. 9). One such conceptual framework for designing and implementing a Digital Twin in smart and sustainable tourism is shown in Fig. 10. It comprises four key steps: identification of big data sources, data management, Data interpretation, and decision-making.

The rapid advancement of 5G communications technology has already highlighted its limitations and the need for the next generation (6G) technology. As suggested in [73], the coupling of the 6G technologies with digital twins and immersive realities has the potential to impact smart cities and contribute to sustainable development goals. The ultra-reliable low-latency communication enabled by 6G will be crucial for autonomous vehicles, optimizing traffic flow, and reducing congestion, leading to lower fuel consumption and emissions [74]. In the energy sector, 6G will facilitate more reliable and more responsive smart grids, enabling real-time monitoring and control of energy generation and distribution, promoting the integration of renewable sources and enhancing energy efficiency [75]. Moreover, 6G will empower the tourism industry by supporting immersive technologies and personalized experiences [76], while fostering sustainable practices through efficient resource management and reduced environmental impact [77].

In that context, the utilization of digital twins with advanced 5G/6G communications technologies can improve sustainability in natural resource monitoring by predicting and promptly addressing potential energy waste and maintenance issues, thus enhancing profitability and preserving environmental resources [78], which is key for sustainable tourism. Digital twins, combined with information and communication technologies and data analytics like artificial intelligence, can help conserve physical resources in the infrastructure industry by enabling new ways of designing, constructing, operating and monitoring infrastructure assets [79]. Moreover, digitally enhanced disaster risk reduction practices that promote civic engagement and evidence-based decision-making can help areas suffering territorial imbalances to achieve sustainable development. The concept of Territorial Digital Twins (TDTs) illustrates the potential benefits of networking distributed information resources in Italian inner mountain areas [80].

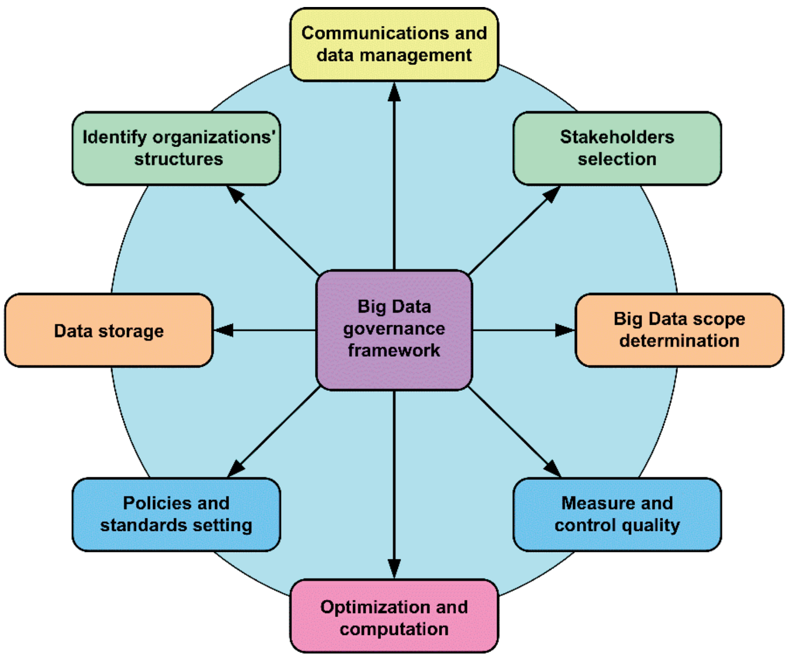


Fig. 9. Big Data governance framework proposed in [72].

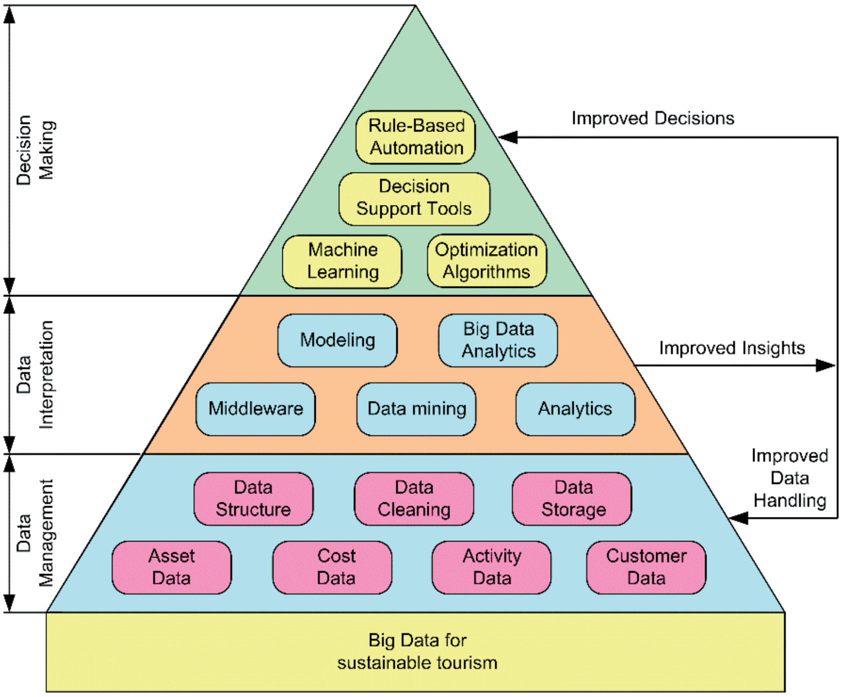


Fig. 10. Conceptual framework of Digital Twin for smart sustainable tourism proposed in [72].

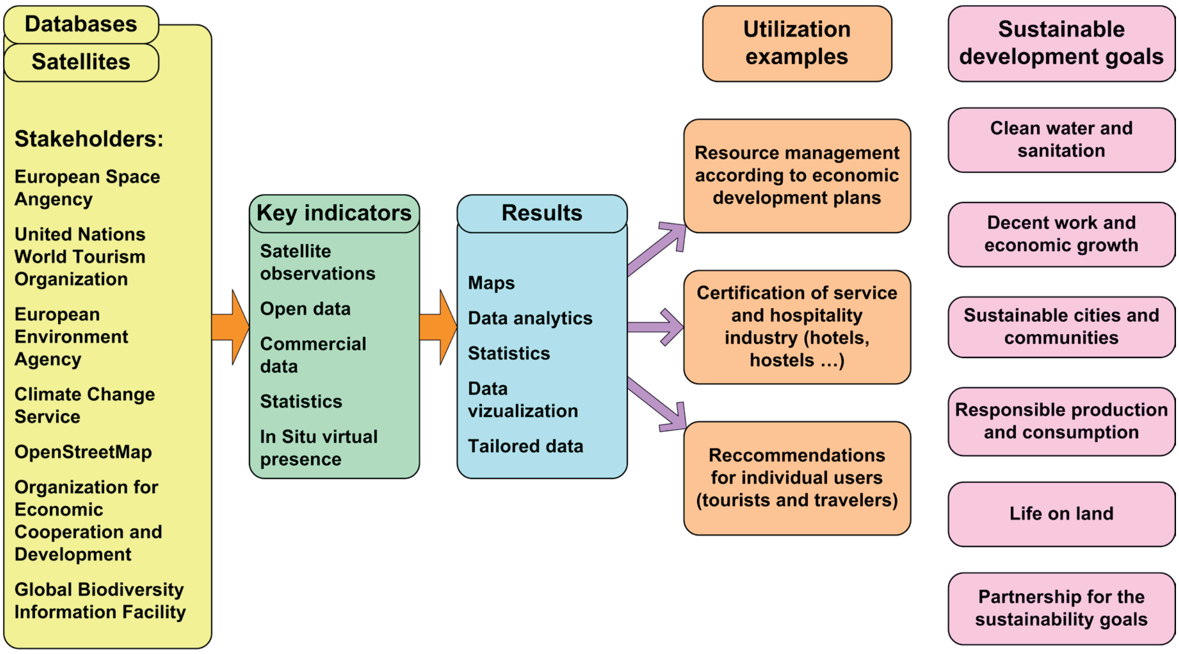


Fig. 11. Conceptual framework of ESA/Murmuration Co. solution for monitoring the impact of tourism on the environment based on satellite data [86].

The concept of lifestyle can be integrated into travel models to better understand behavior. Lifestyles, shaped by opinions, social status, and preferences, influence travel choices beyond just price and convenience, and, thus by considering lifestyles as dynamic rather than static can offer insights into promoting more sustainable travel patterns [81]. Regarding the use of 5G/6G technologies, mobile phone applications can be used to promote sustainable travel behavior. While there are indications that such behavior change support systems can be effective, more robust studies are needed to draw definitive conclusions [82]. Understanding the triggers for sustainable behavior while traveling is crucial for the tourism industry. Research on Canadian tourists found that sustainable consumers often exhibit altruism, frugality, and pro-ecological behavior in daily life, but these behaviors may not always translate to their travel habits [83]. Tackling complex socio-technical systems, particularly in tourism, requires design-driven innovation beyond e-commerce advancements, which is crucial due to tourism's impact on a global and local scale, and the need for a sustainable, regenerative approach. Realizing this goal requires creating holistic solutions that consider stakeholders, leverage data, and create both digital and physical products to enhance sustainable travel experiences [84].

When analyzing the technical regional sustainable reports, it was concluded that it is not possible to comprehensively analyze and compare the data by region for the following reasons: Regions used different sources to analyze the same indicator and had different preferences in the choice of source to be used (European or national/regional sources); and the units of measurement used are not always consistent (some regions prefer absolute numbers, while others use percentages or rates, etc.) [85].

The European Space Agency and the French company Murmuration from Toulouse are developing a solution for monitoring the impact of tourism on the environment based on satellite data (Fig. 11). The solution provides environmental monitoring and forecasting KPIs for the tourism industry on air quality, green areas, urbanization, and water resources, which are collectively expressed as the Tourism Sustainable Development Index (TSDI) [86]. The services are intended for decision makers who want to understand, monitor, report and act on the environmental impact of the tourism industry. The main functions are to provide indicators based on satellite Earth observation data, combine these data into a comprehensive set of indicators that will then be used together with additional data sources and external databases to assess the sustainability of tourism and the impact of these activities on the environment [87]. The indicators will enable decision makers to comply with increasing regulatory requirements for monitoring, controlling, and acting in accordance with the environmental impact of the tourism industry.

In tourist regions with large tourist traffic, it is necessary to create solutions with a system of indicators that can be mapped on multiple scales, and which can help in locating and describing pressures on the environment, thus promoting environmentally friendly destinations or to identify land management policies that can improve the interrelationship between ecosystems and tourism. To produce the above information, Murmuration Co. integrated biophysical, climatic and tourist sector indicators. Table 1 summarizes the indicators that can be monitored by collecting and analyzing data from the European Space Agency's satellites.

5. Discussion

The integration of digital twins (DTs) and Environmental, Social, and Governance (ESG) methodologies presents a transformative opportunity for the tourism sector, which is heavily reliant on the transportation and energy sectors, both significant contributors to environmental impact. DTs, powered by artificial intelligence (AI) and the Internet of Things (IoT), offer a promising avenue for achieving sustainability goals by optimizing resource allocation, predicting system responses, and facilitating data-driven decision-making.

In the transportation domain, DTs have shown potential for optimizing traffic flow, public transportation systems, and infrastructure management, leading to reduced emissions and improved energy efficiency. Furthermore, integrating DTs with blockchain technology can address data redundancy and enhance security in vehicular networks, fostering a more resilient and sustainable transportation ecosystem. However, the successful implementation of DT-driven solutions requires careful consideration of regulatory compliance, stakeholder communication, and data security issues. The energy sector also stands to benefit significantly from DT-ESG integration. DTs can be leveraged to optimize energy production and consumption in hotels, a major energy consumer within the tourism industry. Additionally, DTs can facilitate the integration of renewable energy sources and enable intelligent energy management systems for smart cities, contributing to reduced carbon footprints and increased energy efficiency.

Table 1. *Overview of proposed indicators to be monitored by collecting and processing European Space Agency's Earth observation satellite data [87].*

Indicator	Description
Air	Groups all information for assessing and monitoring air conditions
Biodiversity	Brings together all indicators for assessing and monitoring the state of biodiversity
Climate	Integrates all indicators for assessing and monitoring weather and climate conditions
Human activity	Integrates all indicators for assessing and monitoring the impact of tourism on the environment
Land	Groups all indicators for evaluating and monitoring the state of the ground
Water	Groups together all indicators for assessing and monitoring the state of water resources

However, the adoption of DT-ESG solutions faces several challenges. The transition to sustainable transportation requires not only technological advancements but also a fundamental shift in traveler behavior and preferences. Understanding the psychological aspects of travel choices is crucial for designing effective policies and incentives that promote sustainable practices. Additionally, ensuring equitable access to sustainable transportation options and aligning technological advancements with ESG principles remain critical areas for future research and development.

Digital twin technologies hold significant potential for personalizing incentives and providing real-time feedback to tourists on their environmental impact. For example, a DT-powered app could track tourists' behaviors and preferences such as through historical data, using those data for designing tailored incentives that promote sustainable choices. Moreover, it would be possible to provide instant (real-time) feedback on the environmental impact of their actions, such as those related to transportation and energy use, which can empower tourists to make more sustainable decisions. Naturally, in all those instances it would be crucial to address privacy concerns and ensure transparency in data collection and usage. This can be done by data minimization, i.e. collecting only the data that is necessary for the intended purpose and data anonymization and pseudonymization. Implementation of strong security protocols to protect data from unauthorized access, use, disclosure, disruption, modification, or destruction would be mandatory. This includes encryption, access controls, and regular security audits, and limited data retention, including policies and secure disposing of data when it is no longer needed. Implementing digital twins in the tourism sector also requires careful consideration of various regulations, primarily those pertaining to data protection and privacy, as discussed above. The General Data Protection Regulation (GDPR) [88] introduced in the EU has a global impact and sets strict rules for collecting, processing, and storing personal data. Key aspects include obtaining explicit consent, ensuring data security, and granting individuals rights to access and control their data. While not legally binding, adhering to industry standards and best practices for data governance and security can help build trust and demonstrate a commitment to responsible data handling.

6. Conclusion

This paper outlines the transformative potential of integrating digital twin (DT) models with ESG principles to achieve significant advancements within the transport and energy sectors. By leveraging real-time data and insights generated by DTs, decision-makers can optimize processes, promote resource efficiency, and ensure social equity in these critical domains. Such a strategy is essential for driving global sustainability efforts and addressing our planet's most pressing environmental challenges. While this combined approach offers substantial benefits, its successful implementation hinges on addressing several key challenges. Ensuring the availability, quality, and security of vast amounts of data within the complex DT ecosystem is of paramount importance. Additionally, developing universal standards and governance frameworks will foster compatibility between various DT systems and enhance transparency in ESG reporting. Overcoming these obstacles will unlock the full potential of DT-ESG integration.

In conclusion, the integration of digital twin (DT) technology with environmental, social, and governance (ESG) principles offers a promising pathway towards a more sustainable and resilient tourism sector. DTs have the potential to revolutionize transportation and energy management, two critical components of the tourism industry, by optimizing resource allocation, reducing emissions, and promoting social equity. However, the successful adoption of DT-ESG solutions requires addressing challenges related to data governance, regulatory compliance, stakeholder collaboration, and traveler behavior. Future research should thus focus on overcoming these challenges and further exploring the applicability of DT-ESG solutions across diverse industries and domains. Moreover, when discussing the pivotal role of policy in facilitating sustainable tourism development, one of the key limitations may be the reliance on secondary research. Future research should thus also prioritize the collection and analysis of original data, potentially by focusing on specific case studies, for instance by calculating the total energy savings realized after implementing a smart energy-transport system at the particular tourist destination. This would provide tangible evidence of the policy's impact and further validate the benefits for both tourists and the local population, thus ultimately contributing to a more holistic understanding of sustainable tourism practices.

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Two-level energy planning approach for smart islands energy systems development

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Abstract

Energy planning of islanded systems has always presented a challenge due to their weak connection with the mainland. In order to tackle this issue and make transition of islands energy systems to autonomous, secure and low-carbon systems it is necessary to take into account local needs and resources as well as pay attention to security of electric power system. Two-level energy planning approach presented in this paper provides unambiguous solution to this challenge. Several energy planning scenarios were developed with RenewIslands method and modelled with energy planning software in order to research how integration of transport and energy production facilitate the transition to 100% energy self-sufficient island. Developed scenarios are subjected to load flow analysis that was performed in load flow tool. Research was conducted on island of Vis in Croatia and the results showed that Vis exports 6.8% of its production in HighRES scenario as opposed to LowRES scenario where it is 100% dependent on import. Implementation of parking lot for electric vehicles on island of Vis allowed more control and lowered the voltage values on observed node 45 from 10.3 kV to 10.18 kV for RES scenario.

***Keywords**: Energy planning, Smart islands, Load flow, Electric vehicles, Smart Grid.*

1. Introduction

Introducing renewable energy sources (RES) and integrating energy demand of domestic heating, cooling, fuels for transport or larger, commercial demand is becoming one of the most investigated ways of making local island communities more energy self-sufficient. Also, once the larger integration of RES is achieved, it is important to properly understand and quantify the influence of RES and demand response technologies on local electricity distribution network, in order to plan timely upgrades. Unlike conventional approaches that primarily optimize energy balances, this methodology explicitly evaluates the feasibility of integrating high shares of renewables within local grid constraints by considering voltage stability, power flow limitations, network congestion, and dynamic interactions between renewable generation and flexible demand resources. By incorporating load flow analysis, the approach provides insights into potential voltage violations, grid bottlenecks, and power import/export constraints, enabling early-stage identification of technical challenges. Furthermore, the methodology assesses the role of demand-side flexibility measures, including sector coupling and vehicle-to-grid (V2G) interactions, in mitigating these challenges and enhancing grid resilience without extensive infrastructure reinforcements.

In energy planning of small island energy system, integration of other systems, like transport, requires particular care and precision due to lack of resources and space restrictions. The proposed methodology is designed to be adaptable to different island contexts, considering variations in resource availability, grid constraints, and energy demand patterns. By integrating scenario-based energy planning with grid feasibility analysis, this approach can be tailored to islands with diverse renewable energy potentials, different levels of interconnection, and varying degrees of energy autonomy. Regarding comprehensive planning of island energy systems, research was focused on developing methodologies like RenewIslands methodology for resource and technology planning in [2]. In [1] a sophisticated model was developed, linking spatiotemporal capacity planning with power flow analysis, to enable better integration of renewable energy sources into the power systems of island communities. The importance of storage technologies, energy efficiency and energy savings for RES integration was studied with an island of Hvar as a case study, which was conducted in EnergyPLAN software in [4]. Research on the potential for implementing floating solar panels on water reservoirs shows significant promise for additional energy storage and increasing the share of renewable energy [5]. Also, H2RES software was used in [6] on a case study of Cape Verde to integrate energy and water supply. Sector integration impact on the electricity demand curve was studied in [7]. A study on the digitalization and development of smart islands in the Kvarner archipelago demonstrated how digital technologies can enhance energy self-sufficiency through sector integration and improved energy management efficiency[8]. Other software solutions were used in [9] for large island communities. Optimization strategies for integrating renewable energy have advanced significantly with the use of hybrid energy storage solutions, which enhance system reliability and stability [10]. Various combinations of RES and hybrid systems on isolated islands were studied in cases of Porto Santo [11], San Vincente and Cape Verde [12]. The economic implications of hybrid renewable energy systems were analyzed, emphasizing their role in enhancing energy security and promoting sustainable economic growth in small island communities [13]. For smaller island, in the case of environmental restrictions, penetration of RES was studied in [14] In case of integrating wind energy in the electric energy system of Croatia, potential was studied using GIS, in [15]. Regarding the solar energy potential and feasibility, developments and trends, as well as future role of solar PV will play in local and national energy systems was elaborated in [16].

Single and multi-action initiatives, for energy transition of island power systems towards smart islands, were assessed in [17]. Integration of EVs into a microgrid was examined in [18], using an optimization model for managing the energy in a grid-connected smart grid that includes RES and a parking facility for EVs. Another study investigating synergies of EVs and energy production system, where the vehicle to grid (V2G) technology was used is given in [19]. V2G technology was also used in [20] as one of the strategies of demand response and compared to supply side strategies. The authors in [21] modelled EVs as a type of load and compared it to three conventional types of load. A research about integration of transport and energy production sector in the case study area was conducted in [22], discussing also the option for financing the transition. Also, an example of taking the PRISMI approach to the long term planning can be found in [23]. In [24], PLEXOS modelling tool was used to demonstrate that in some cases, for small islands and integrated planning case, smart charging can reach similar effect as V2G. In [25] it was shown, using EnergyPLAN and HOMER tools, that for small islands dump charge and V2G have the opposite effect on electric grid, which is relevant for the present study. In [26], a different approach in choosing the technologies was employed, the polygeneration system, combining electricity and water supply systems, as well as heating and cooling supply was investigated on the case study of Pantalleria island. The research results show that polygeneration approach can fulfil the water demand of the community and supply significant amounts of electricity, heating and cooling energy with acceptable payback period. Replacement of fossil fuel with solar power, i.e. electricity generation from rooftop photovoltaics for the case of Canary Islands was studied in [27]. A study [28] evaluated the long-term energy planning impacts of demand response and reserves on islands, highlighting the importance of these strategies. However, it did not investigate grid conditions under their application, which is a crucial aspect to consider. The aim of research in [29] was to show how it is possible that photovoltaic systems can help with existing power quality problems in network. Even though PV systems are said to be the cause of many disturbances due to their variability, operational results are in contradiction to hypothesis that they can not also offer the improvement of energy quality. Regarding the economic implication of various options, study [30] investigated economic sustainability of hydrogen and battery storage implementation on small islands. In this research, the aim was to use the synergy between power production and transport sectors for storage and balancing.

Taking this line of research a step further, an investigation of connection in the archipelago and influence of demand response technologies on the interaction between the island systems, is conducted in [31]. Once the energy systems are modelled with energy planning tools on hourly level, there is still one step which needs to be taken, namely load flow analysis to investigate the ability of local distribution network to accommodate new installation. In a study [32] planning process which models a power network taking into account detailed information on the power network including the location and capacities of generators, consumers, substations, and power lines was investigated. The load flow (LF) calculation method is perhaps the most widely used method for analysing electric power systems [33]. It appears in several variations and in all of them the objective is invariably the same: to solve the steady-state operation of the grid by calculating the node voltages and currents. Among the various LF solving techniques used in research studies we can distinguish the methods of Gauss-Seidel, Impedance, Piecewise Impedance, Newton-Raphson (NR), PQ-Decoupled method, DC Load-Flow, Optimal Power Flow (OPF), as well as other more sophisticated algorithms that make use of different approaches like. Artificial Intelligence, Genetic Algorithms, Artificial Neural Networks, Fuzzy Logic, Probabilistic Analysis, Mixed Integer-Linear Programming etc. In [34] the authors used Artificial Neural Networks, in [35] the approach was tried with conventional and neural networks. Further on, [36] employed fuzzy logic for load-flow analysis and in [37] probabilistic analysis was used. Finally, in [38], a reconciliation algorithm was used to model optimal power flow with reactive power in realtime for the case of dispatch of wind stations. It is worth noting that most LF-related research studies refer to large-scale electricity grids due to their complexity as opposed to island power systems which are simpler structures and do not require sophisticated analysis methods. As a consequence, there is rather limited literature in terms of using LF tools for the analysis of small power systems. A case in point regarding the use of LF in the analysis of small-scale and island power systems is the reference [39]. Unlike transmission system networks, distribution system networks are characterized with high R/X ratio as well as radial structure. This can cause convergence problems when the load flow calculation is performed with traditional load flow algorithms. To solve this problem and increase the efficiency of solving distribution system load flow, alternative algorithms have been developed. Mekhamer et al. [40] proposed method which avoids formulation and calculation of Jacobian matrix which reduces the time of calculation and uses less computer memory. In order to shorten the calculation time, a effect of mutual coupling is achieved by using equivalent branch voltage sources or bus current injections in [41]. Another method for solving networks with high R/X ratio is presented in [42], where authors use constant Jacobian matrix with need of only one factorization. A Polar Current Mismatch Version of Newton Raphson which uses polar coordinates for current mismatch functions is presented in [43]. This study uses tool presented in [44] that offers a possibility to calculate electrical grid voltages and load flow as well as visualise electrical grid on geographical island.

The aim of this paper is to demonstrate two-level approach planning of the energy system, in which first step is to model the future outlook of the energy system and then to investigate energy flows in local distribution network, which appear as a consequence of installed technologies. Such approach represents contribution by enabling the possibility to investigate impact of different energy planning scenarios on the electric power grid and which was not possible in several mentioned studies. Possibility of identifying voltage and line capacity violations in electric power grid can lead toward need for either lowering the amount of RES integration, upgrading the electric power grid or using new technology for voltage control. This study investigates the possibilities for improving the voltage conditions in grid by integrating different sectors, namely energy and transport sectors, by implementing EV parking lots with smart charging and discharging.

Batteries of parked EVs can be considered as an aggregated battery with variable capacity, depending on the number of vehicles that are currently on the parking and state of charge (SOC) of the vehicles. V2G provides demand response services, or in other words, EV parking lots can function as a load or generation depending on electricity distribution system requirements.

In chapter 2, methods used in this research are elaborated. Further on, in chapter 3, a case study is described, while in chapter 4 the results of the new approach are elaborated and discussed. Conclusion is given in chapter 5.

2. Methods

During this research, the PRISMI approach, which was developed during the PRISMI Interreg MED project, adding on the RenewIslands methodology (on which it is based) through improved approach, using GIS mapping of resources and load flow analysis, was employed. Steps of the PRISMI approach, employed in this paper, are:

1) Mapping the needs of the island community
2) Mapping the locally available resources
3) Technologies overview for bridging the gap between needs and resources
4) Division of scenarios

Energy system development of any particular island is examined in three main scenarios, of which third one is modular:

LowRES – following the same dynamics of RES use, as already proposed in actual SEAP-s or other available documents

RES – Increase of RES use, with taking into consideration environmental constraints and legislative framework, which is dependent on location of any case study and potential implementation of technologies which offer synergetic effects with other sectors.

HighRES – Modelling for a 100% RES energy system of the island, in this case taking into account possibilities of sub-scenarios of using the wind energy (HighRES wind) and a case without wind turbines (HighRES) and using the synergies with other sectors. This scenario is modular in terms of use of wind energy, but always aims towards 100% RES supplied energy system.

Scenarios are then calculated using EnergyPLAN software, in order to get hourly results of production from all technologies, as well as discharge from storages, in order to balance the system, aiming to achieve a self-sustainable system.

5) Load flow analysis using the tool developed to be user friendly and quickly indicate the issues arising in the grid. The LF tool was developed using purely Matlab® coding and its validation was done by benchmarking it against reference models in Matlab/Simulink. Once the development phase of the tool was finished with the use of Matlab/Compiler a standalone application was generated in order to facilitate the tool usability. Important assumptions are that electric power grid is in steady-state condition, that the operation of the grid is balanced and that the voltages and loads are symmetrical for all three phases of the system. Since LF is the next step of this approach, it can include case analysis in terms of locations of production and consumption facilities proposed by scenarios from the energy system modelling step of the approach. LF tool is used to simulate possible impacts on technical aspects of the grid, primarily voltage and power import/export, by implementing new technology in the distribution grid. Such technology may include different kind of demand response such as desalination plant, EVs, electric boilers or batteries.

In order to use the load flow tool as a final step in modelling of the energy system following data of the electricity distribution system layout and characteristics is needed:

- Buses (nodes)
- Line parameters
- Transformers
- Connectivity of generators and loads to buses
- Active/Reactive power profiles for each bus
- Control method/behaviour:
- Voltage set-points of buses
- Voltage limits of each bus
- Line Capacity limits
- Reactive Power limits for PV generators
- Active Power lower limits of conventional generators

The proposed LF tool is provided in the form of a standalone executable application, and uses grid, generation, and consumption data as inputs from previous steps of the PRISMI methodology to calculate the grid voltages and currents. It combines a number of features useful for the proposed method, minimal requirements in terms of input parameters and algorithmic implementation make the tool user-friendly.

This calculation is done by using the NR solving method which is characterized by good convergence on small distribution grids as is case on islands. The goal of NR method in the aspect of power systems is to calculate voltages (Ui) and voltage angles (δi) of every node in electric power grid by solving nonlinear equations into problem of repeatedly solving linear equations while knowing parameters of the grid expressed with admittance matrix (Y). Real power (Pi) and reactive power (Qi) at node i are defined with equations (1) and (2), where n is total number of nodes, g is number of generation nodes, θ_{ij} is phase angle difference between nodes i and j and Y_{ij} is element of admittance matrix or admittance between nodes i and j.

$$P_i = U_i \sum_{j=1}^{n} U_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \qquad i = 1,2, \dots , n - 1 \qquad (1)$$

$$Q_i = U_i \sum_{j=1}^{n} U_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \qquad i = 1,2, \dots , n - g - 1 \qquad (2)$$

The tool is equipped with Human Machine Interface (HMI) that allows the user to perform a number of actions such as:

- Select the grid to be analysed. The user can select among a number of pre-set models or to specify their own data.
- Specification of the timeframes to be calculated depending on the available input data.
- Simplified drawing of the selected grid in order to check the correctness of the input data.
- Modification of the operating voltage and capacity limits.

Also, as outputs the tool provides the user with information about the voltage/capacity limits violation as well as a graphical illustration of all the problematic and normal parts of the grid.

Two-level energy planning of islands is presented and tested in this paper.

Hypothesis of this study is that, with presented two-level approach, it is possible to create and validate different energy planning scenarios in steady-state operation of the grid and indicate the appropriate locations for new installations in the grid or possible needed updates of the grid. First level analysis provides framework for energy planning by creating several different scenarios while the second level analysis presents technical feasibility of energy planning scenarios in the context of local electricity distribution system. The modelling of scenarios in second level is done for characteristic periods of the year, where a special emphasis is placed on investigation of power import and voltage profiles.

3. Case study

The island of Vis is a small Croatian island in the Adriatic Sea, with an area of 90.3 square kilometres and it is the farthest inhabited island off the Croatian mainland, with a population of 3,617 in 2011, concentrated in two larger towns, Komiža and Vis, both around 1,500 inhabitants. The highest point of the island is 587 meters above sea level. Once known for its thriving fishing industry in the late 19th and early 20th century, the main present-day industries on the island are agriculture and tourism. Concerning island's electrification, Vis currently depends on a submarine cable with the island of Hvar, which supplied 17 GWh of electricity to the island of Vis in 2016. Vis Island was selected as a case study due to its unique energy characteristics, including its limited interconnection to the mainland grid, high renewable energy potential, and growing need for energy self-sufficiency. These factors make it a representative test case for assessing the feasibility of high-renewable penetration in constrained island energy systems, which often face similar infrastructural and regulatory challenges. Resources charted through the PRISMI method are given in Table 1.

Regarding the possibilities of installation of solar PV on the island of Vis, the surface of all residential area of the city Komiža is estimated to be 108,000 m^2. Solar potential mapped and presented through PRISMI GIS geo-database is illustrated in Fig.1.

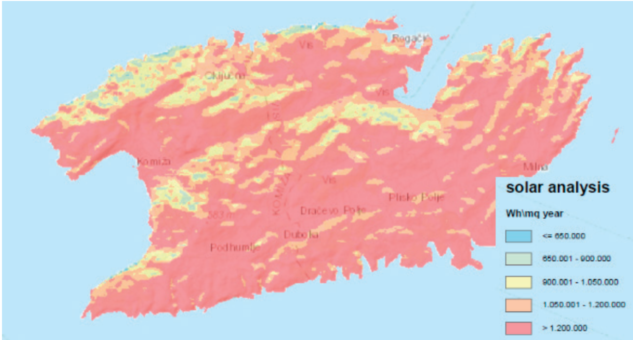

Figure 1. GIS map of solar potential on the island of Vis

After taking into account the orientation of rooftops, possible protection of cultural heritage and other restrictions, the possible surfaced is estimated at approximately 32,500 m^2. This surface gives the possible maximum nominal power for installed PVs of 5,000 kW in Komiža and approximately the same for the town of Vis.

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The simulation takes also into account the 2 MW solar power plant that is planned on the island of Vis. Other relevant resource is wind power, but the exploitation is made difficult due to the island being completely covered by the NATURA 2000 network and protected. Table 2. lists all input values for calculation of scenarios for the energy system and transport system on the island of Vis in the year 2030 [45]. As a reference model, energy system of the island of Vis was also modelled in EnergyPLAN for the year 2016, with known electricity load and other data on consumption calculated from documents available online (official documents of local government), as well as from previous research in [22] and [45].

The number of vehicles vary depending on period of the day as well as the period of the year. Because of many tourists' arrivals in the summer months, the average arrivals to the parking lot are two times higher than in the winter months. Therefore, the EV parking model presented in this paper is considered for two months – July and February. The EV parking lot is placed in node 47 in town Komiža. The day is divided in four periods depending on whether the vehicles are arriving or departing from the parking lot. The arrival periods are from 6am to 12pm and from 18pm to 21pm, while departure periods are from 13pm to 17pm and 22pm to 5am. Detailed schedule of number of parked vehicles is presented on Fig. 2.

The characteristics of EV parking lot are taken from [18] and presented in Table 3, with the exception of setting more strict constraints for minimum SOC.

From the presented data, it is possible to calculate that during one hour an EV can discharge to the grid a maximum of 12 kW and charge from the grid a maximum of 16 kW. Therefore, by multiplying number of parked EVs with maximum charge and discharge power it is possible to present EV parking as a battery with changing capacity according to the Fig. 3., which shows possibilities for charging and discharging during summer and winter months.

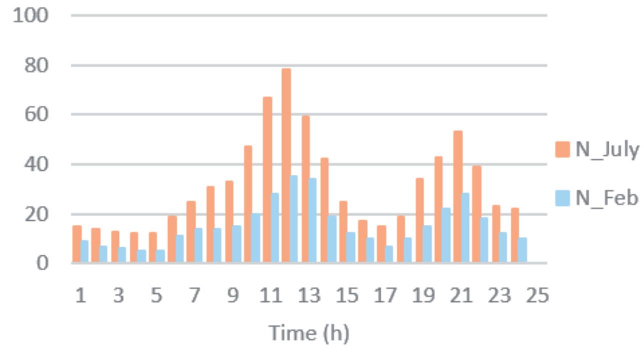

Figure 2. Schedule of number of parked vehicles

Table 1. *Resources on Vis*

Local primary energy			Energy import infrastructure			Water		
Resources	Level	Code	Resources	Level	Code	Resources	Level	Code
Wind	Medium	WindM	Grid connection	Normal	GridN	Rainfall	Low	H2OPL
Solar	High	SolarH	Natural gas pipeline	None	NGplN	Groundwater	Normal	H2OGN
Hydro	Medium	HydroM	Terminal LNG	None	LNGtN	Water supply	Yes	AquaY
Biomass	Medium	BIOMM	Oil terminal/ refinery	None	OilRN	Seawater	Yes	H2OSY
Geothermal	Low	GeothL	Terminal petrol production	None	OildDN			

Table 2. *Input data for calculation in 2030 for all scenarios and sub-scenarios*

2030	LowRES	RES	HighRES wind	HighRES
PV [MW]	1	10	12	12
Wind [MW]	0	0	3.5	0
EV [nr. of vehicles]	0	617	1234	1234
EV connection [MW]	0	1.985	9.131	9.131
EV demand [MWh]	0	1778	2767	2767
EV battery [MWh]	0	14.496	48.126	48.126
Electricity demand [MWh]	17690	19290	21180	21180

Table 3. *Parameters of EV parking*

Parameter	Value
EV battery capacity	40 kWh
Average SOC of parked EV	50%
Minimum SOC allowed	20%
Maximum SOC allowed	90%
Charger capacity	20 kWh

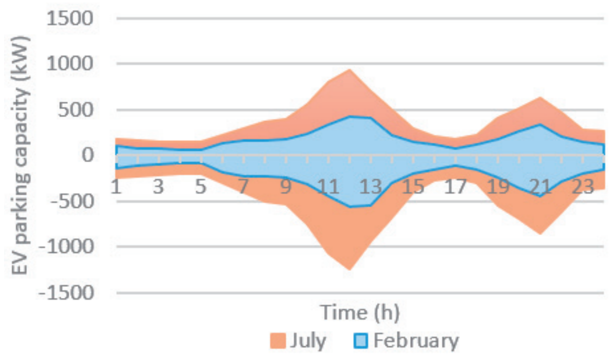

Figure 3. Capacity of EV parking lot

4. Results

4.1. Results of modelling of the islands' energy system in EnergyPLAN

Results of the calculation in EnergyPLAN demonstrate how increase of RES integration and synergy with electrified transport system gradually take over the supply of electric energy for the island of Vis. For the LowRES scenario, represented by Fig. 4, solar PV covers for only minor amount of energy needs. In case of RES scenario, solar PV covers for the majority of demand, but there is still need for electricity import.

At the same time, there is significant share of energy supply in the form of discharge from the batteries of electric vehicles, represented as "V2G" on the Fig. 5.

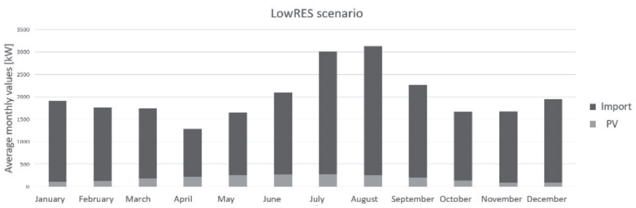

Figure 4. Results of LowRES scenario as monthly average hourly production of electricity

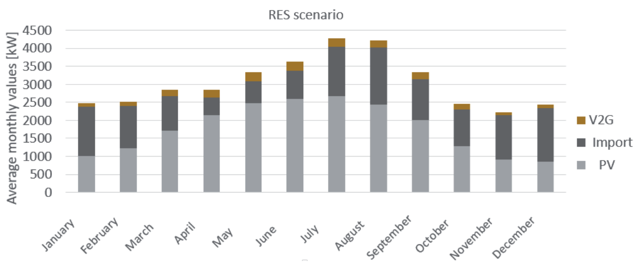

Figure 5. Results of RES scenario as monthly average hourly production of electricity

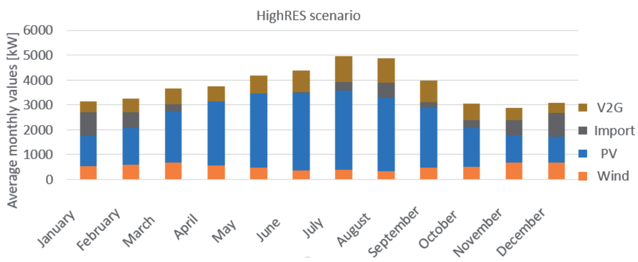

Figure 6. Results of "HighRES wind" scenario as monthly average hourly production of electricity

When two RES technologies are used, as in the case of HighRES scenario with wind power (located in node 41), then almost all of the energy demand is supplied by the local sources and supported with EV batteries for demand response and storage, as demonstrated in Fig.6. Only during winter months and high tourist season there is minor need for import.

In this scenario, synergies between electrified transport and energy production sector is most visible, through many hours of EV batteries discharging energy back to the grid (Fig. 7).

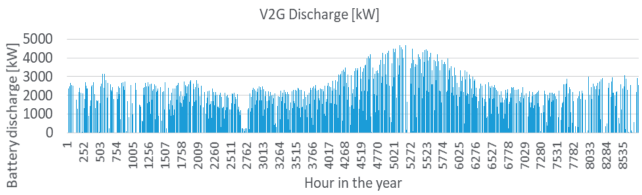

Figure 7. Discharge from electric vehicle batteries

In case only one technology remains the only choice, import will remain significant during the winter and in high tourist season, as it is visible in the Fig. 8, representing HighRES scenario without use of wind power. Results of all scenarios are given in Table 4.

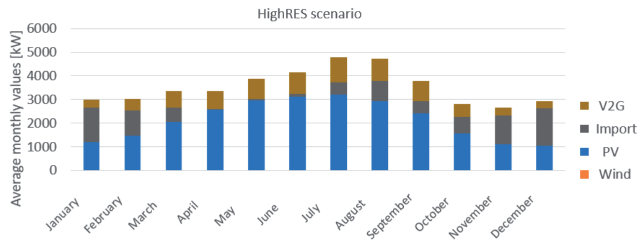

Figure 8. Results of "HighRES" scenario as monthly average hourly production of electricity

4.2. Results of use of load flow tool on the islands' electricity distribution grid

After supplying the tool with data on configuration and data regarding the grid's performance, model of the grid, obtained in such way, was used to test the grid's stability and performance for all the scenarios described above, in characteristic days of the year. The electricity distribution grid of island of Vis is presented on Fig.9. From the LF analysis point of view the following assumptions have been made:

-Part of the line parameters were based on datasheets corresponding to the actual lines, whereas other parameters were based on existing literature models with similar characteristics.

-All distribution (MV/LV) transformers were lumped with the loads at MV level.

-Node no. 38 is assumed as the swing bus of the LF calculation. Apart from keeping the voltage magnitude of it at 1pu (10kV) the specific bus also determines the amount of import/export power as it is the interconnection-to-mainland point of the grid. The assumption of the voltage control of node 38 results in rather limited variations in the voltage profiles in most of the scenarios.

-The loads and EVs are proportionally distributed among the nodes based on the nominal capacity of each distribution transformer.

As an implementation example, in Fig. 10 and Fig. 11 two days in July, at the peak of the tourist season, when the demand is at the highest level, are presented in terms of voltage level and power import in each hour. The figures present node 45, which is located in the town of Komiža and is the beginning of the line connecting Komiža and the town of Vis. It is visible on the Fig. 11 that the island of Vis is continuously in need of import and on voltage levels below nominal in the base and LowRES scenario, while HighRES scenarios differ in voltage levels and export profiles in the middle of the day. This demonstrates the sensitivity of the tool for the different conditions in the grid, caused by integration of different RES technologies and electric vehicle's batteries. Results of the analysis show that during summer the minimum and maximum voltage and power import amounts are in base and RES scenario. Further penetration of RES in HighRES and HighRESnWG scenarios lowered the maximum values and increased the minimum values of voltage and power import. For example, it is possible to observe that for July the peak voltage value in node 45 has decreased from 10.28 kV in RES scenario to 10.2 kV for HighRESnWG scenario and 10.18 kV for HighRES scenario. This effect is more visible for HighRES scenario with wind which indicates that implementation of different RES technologies such as wind, solar and EVs in this case create better voltage conditions in the grid.

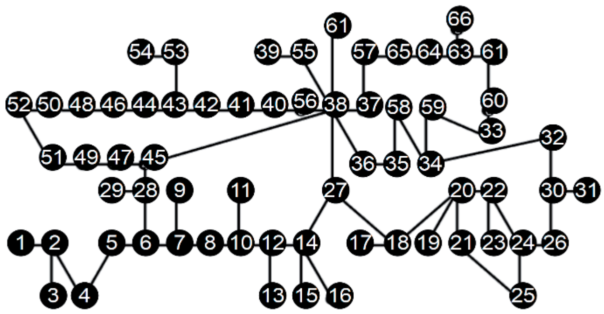

Figure 9. Grid configuration introduced into the LF tool, representing the DG of the island of Vis

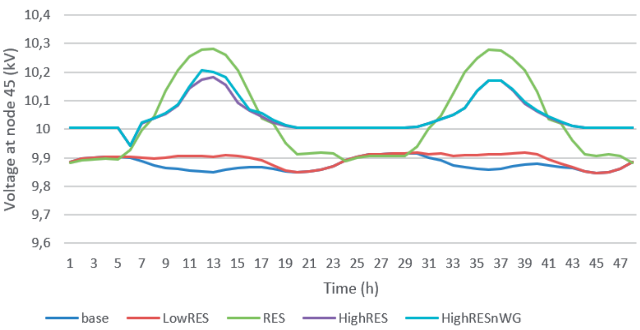

Figure 10. Voltage variation at node 45 during two days in July

In another time of the year, represented by Fig. 12 and Fig. 13, during the winter, the demand is lower than during summer, which is why the need for import of energy is lower and voltage values higher in the base and LowRES scenario (Fig. 12). Voltage values for all scenarios are in range of 1,5% of nominal voltage which indicates that none of the scenarios is causing any instabilities in steady-state operation of the electric distribution grid (Fig. 13).

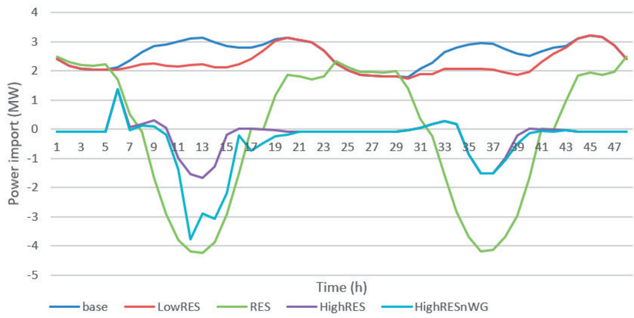

Figure 11. Power import during two days in July

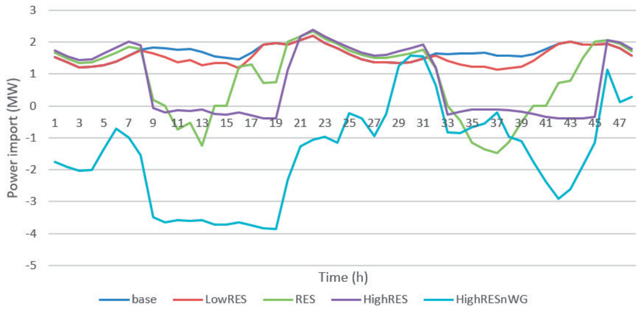

Figure 12. Power import during two days in February

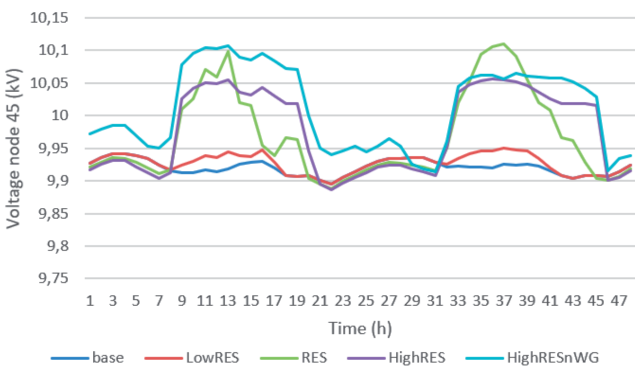

Figure 13. Voltage variation at node 45 during two days in February

In Fig. 14, the final output of the tool is illustrated. The specific output is produced by imposing more rigorous operation limits to the system. In particular, the maximum allowable voltage deviation was set to 1% while the maximum line capacity usage to 50%. In this, way it was possible to show the tools ability to identify potential problems in the grid at midday for the chosen distribution of RES power plants. The result indicates possible problems in the area of the town of Komiža and the location of 2 MW PV power plant in Žena Glava (Node 11), as well as the south part of the island, which consists of a few villages in the south-east part of the grid (all these buses and lines are marked with red in Fig. 14).

This output indicates that the tool provides additional information, which was not realised only through the first level of planning (use of EnergyPLAN tool), namely, that the grid needs to be upgraded in the area of the town of Komiža, if it is to accommodate the installations of 5 MW of solar PV integrated power plants. The possible course of action is to test another distributions of the PV power plants, such as more ground-based plants, reduce the plans of installations to lower capacities or include the upgrading of the distribution grid to the plans. If the lower capacities would be installedfor RES scenario, there would still be problems with the area of the town of Komiža again due to the very strict voltage limit we have chosen. However, in this scenario the line congestion problem between nodes 11 and 10 has disappeared due to the higher allowable capacity of the scenario (85%). The conclusion is that, for the specific operating limits, this part of the grid needs updates in order to accommodate new RES installations on the meaningful scale.

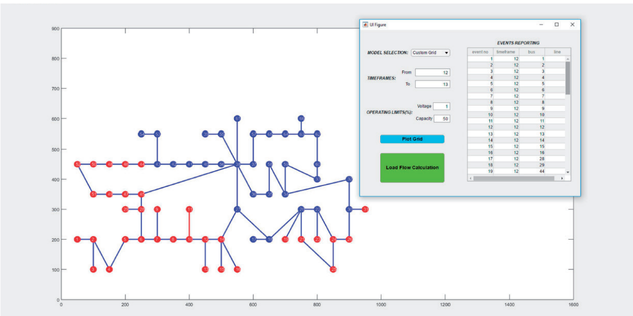

Figure 14. Tool output

Although voltage and line capacity values on Fig. 14 are very strict, it is clearly shown that with two-level approach it is possible to predict local electricity grid problems depending on maximum allowed values of voltage and line capacity. Once the problems are identified, the adjustments can be made in terms of geographical allocation and sizing of the new installations in order to eliminate the problems.

4.3. Concept of using EV parking lot as battery and its influence on electric distribution grid

This paper presents special form of V2G concept by modelling the parking of EVs. As mentioned before, EV parking lot is considered as a battery that changes capacity over time depending on the number of vehicles that are currently on the parking and SOC of the vehicles.

The impact of EV parking lot on power import and export during two days in July can be observed at Fig. 15 and Fig. 16. It is possible to notice that for HighRES scenario (Fig. 16), the installation of EV parking slightly increases power import, but also decreases the amount of exported power. Implementation of EV parking lot also results with lower amounts of variations of power import and export. In RES case during July (Fig. 15), the EV parking lot slightly decreases the amount of imported power, as well as lowers the amount of exported power. These effects represent synergy between solar power generation and EV parking lot, where EV parking acts as a battery stack, combining all the EV batteries connected together at the given location. This is especially visible in the RES case. During peak solar production, EV parking lot increases total demand because it is in charge mode. This leads to decrease of excess power. In periods when there is no solar generation or when the solar generation is low, the EV parking is in discharge mode and provides additional electric energy needed to satisfy the demand.

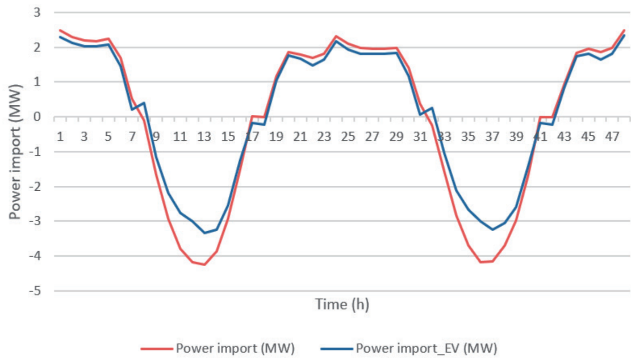

Figure 15. Power import during July for RES scenario

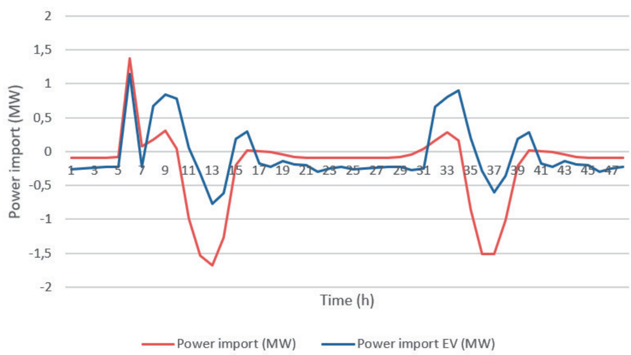

Figure 16. Power import during July for HighRES scenario

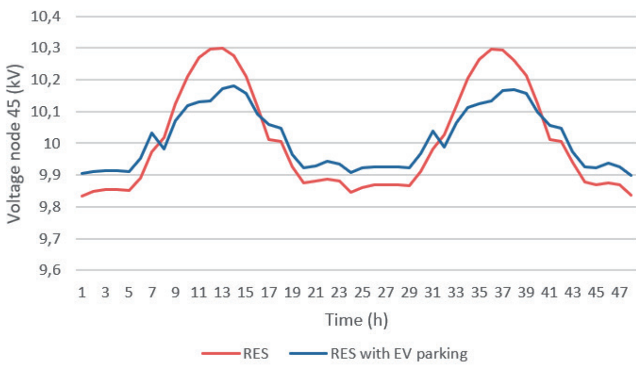

Figure 17. Voltage at node 45 during July for RES scenario

Voltage profiles for nodes 45 are provided on the Fig. 17 and Fig. 18 and for node 5 are provided on the Fig. 19 and Fig. 20. Node 45 is located in Komiža and it is right next to node 47 where the EV parking lot is connected. Node 5 will be used for investigating voltage in part of the grid that is distanced, but still impacted by EV parking lot.

For RES scenario, a very positive impact of EV parking lot is visible on Fig. 17 and Fig. 19. The EV parking lot lowers peak values of voltages during high solar production and raises minimum values during low solar production. The highest voltage value for RES scenario in node 45 without EV parking lot is 10.3 kV, while the highest voltage with EV parking lot is 10.18 kV. This effect is more expressed for node 45 than on node 5 due to geographical closeness of node 45 to node 47. For HighRES scenario (Fig. 18 and Fig. 20), the EV parking lot decreases peak voltage values as in RES scenario, but in this scenario this effect is more visible on the distanced node 5.

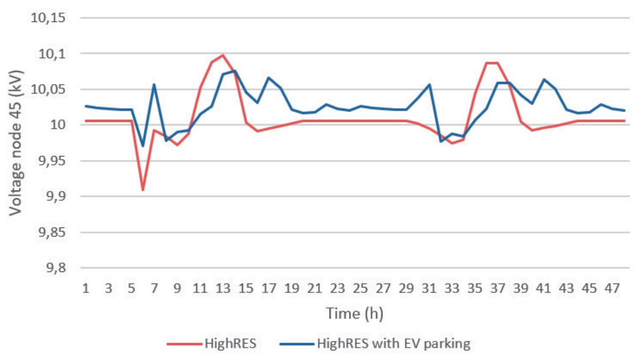

Figure 18. Voltage at node 45 during July for HighRES scenario

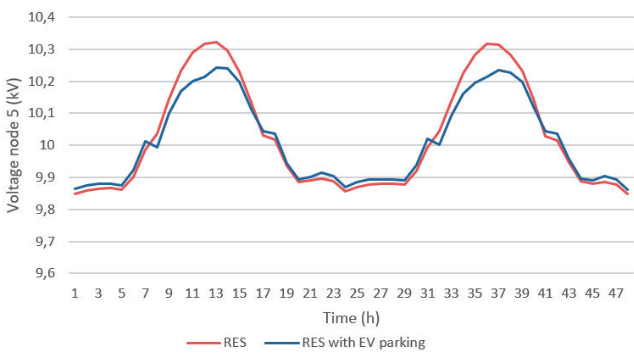

Figure 19. Voltage at node 5 for RES scenario

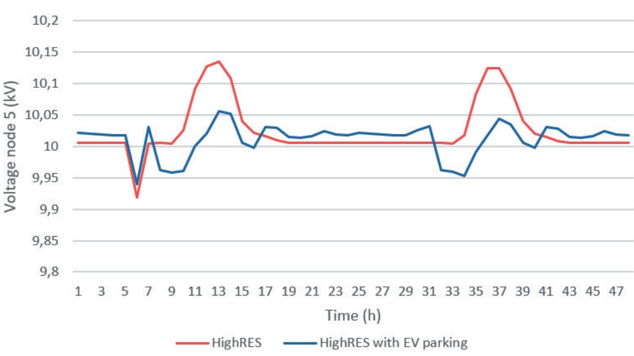

Figure 20. Voltage at node 5 for HighRES scenario

Similar effect is visible during the February on Fig. 21 for RES scenario and Fig. 22 for HighRES scenario. Due to the fact that there is less EVs on the island during winter months than during summer months, the impact of EV parking is lesser in both scenarios. Nevertheless, the impact of EV parking lot is still visible because of the slightly reduced amounts of power import and power export.

Because of EV parking lot impact, the voltage profile during February is also improving. Fig. 23 and Fig. 24 show voltage profiles of node 45 for RES and HighRES scenarios during two days in February, respectfully. EV parking lot improves voltage on node 45 in RES and HighRES scenario so that voltage deviation isn't greater than 1% of nominal voltage 10 kV. Peak values of voltage at node 5 are also improving, except minor fluctuations of voltage occur during solar production in RES case.

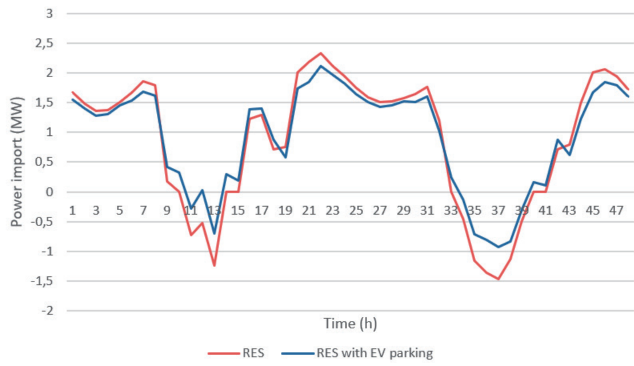

Figure 21. Power import during February for RES scenario

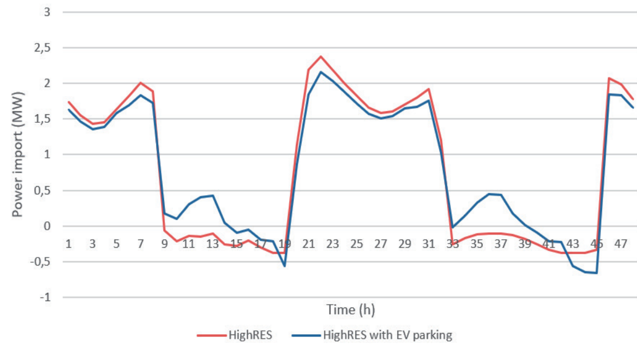

Figure 22. Power import during February for HighRES scenario

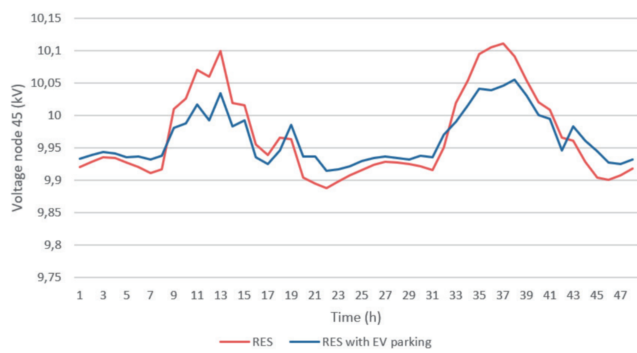

Figure 23. Voltage at node 45 during February for RES scenario

The results indicate that implementation of EV parking lot would have positive impact on grid performance. The impact is more visible during summer months due to higher capacity of EV parking lot. The amount of exported and imported power decreases and the peak values of voltages are closer to the nominal value of 10 kV. The impact of EV parking lot is more visible for RES scenario than for HighRES scenario which shows the synergy between EV parking lot and solar generation. This is because the most of the

EVs is parked during the highest solar generation which results in synchronisation between these two technologies.

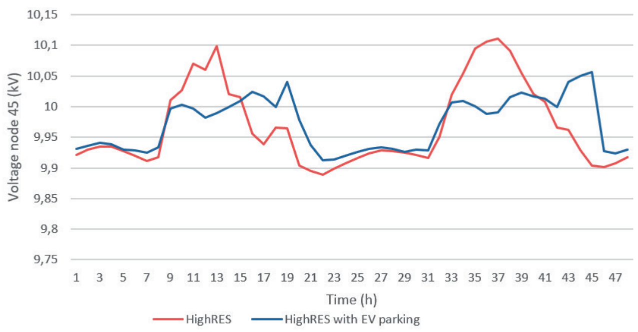

Figure 24. Voltage at node 45 during February for HighRES

Figure 25. Voltage at node 5 during February for RES scenario

Figure 26. Voltage at node 5 during February for HighRES scenario

5. Conclusion

A two-level approach to energy planning of the island's energy systems is presented in this paper. First level provides hourly calculations and solutions regarding the integration of RES technologies and other sectors, such as heat, water and transport sector. In this paper, particular attention in the scenario approach was given to the synergy of RES exploitation and electrified transport as a demand response technology. Results of this step indicate the possibility for the island's energy system to become almost self-sufficient regarding the energy supply in terms of need for electricity and transport needs. This is in particular shown in the HighRES scenarios, which offer continuous local supply of energy from solar and wind power, combined with electric vehicles. It is concluded that with implementation of new technologies and RES it is possible to significantly reduce the islands dependence on power import. The second level of planning involves investigation of the conditions in the electricity distribution grid for all the scenarios examined in the first level. This level offers insight in terms of ability of the present grid to accommodate large installations of RES. On the case study of the island of Vis, for which a model of distribution grid was created in the LF tool, the sensitivity and ability of tool to provide outputs which are helpful in answering the question of distribution of installations within the grid are demonstrated. The results show that in case of the HighRES scenario and with chosen voltage limits, planned installations cannot be placed exclusively in the towns of Komiža and Vis, because it would cause problems in the local grid. There are several possible solutions for resolving this problem. Two possibilities are to upgrade the local grid or to change the layout of the installations across the island and the third possibility is to integrate new technology that will allow voltage control. Thus, in order to tackle the issue, the paper presents model of EV parking lot for island of Vis, located in town Komiža and connected in V2G mode, that is considered as a battery with fluctuating capacity, acting as a typical example of synergy between energy production and storage system and transport system in transition of island's energy system towards self-sufficiency. While this study focuses on Vis Island, the proposed methodology is designed to be applicable to other remote and islanded energy systems worldwide. The insights gained from integrating scenario-based energy planning with grid feasibility analysis can support broader energy transition efforts, particularly in isolated systems with high renewable energy potential and grid constraints.

This kind of approach brings many benefits to the distribution system such as improvement of voltage profile, better frequency control and better electric power quality. Moreover, V2G concept represents clean and sustainable technology that will significantly contribute to power grid transition to low carbon smart grid. The calculation shows that LF tool allows execution of wide variety of scenarios and analysis of impact of these scenarios on different electricity distribution characteristics such as voltage and power import. EV parking can provide demand response to the electric distribution grid in higher or lower amount depending on period of the day and year. The impact of EV parking lot is simulated for RES and HighRES scenarios and the results indicate that EV parking lot has positive impact on conditions in the grid. The imported and exported power is reduced for all scenarios and the voltage levels are closer to the nominal voltage. This is especially visible for RES scenario where the voltage on node 45, located in Komiža, during July is reduced from maximum value of 10.3 kV to 10.18 kV and minimum value increased from 9.83 kV to 9.9 kV. This analysis shows that, with LF tool, it is possible to simulate wide range of scenarios and models to investigate electric distribution system. The proposed two-level energy planning approach provides valuable insights into the integration of renewable energy and grid feasibility on islands. While this study focuses on Vis Island, the methodology is designed to be adaptable to various island systems with different grid structures, renewable energy potentials, and population densities. Future work should focus on testing this approach on islands with varying levels of interconnection, sectoral integrations, and network constraints to further validate its robustness and generalizability. Additionally, applying this method to more densely populated islands or those with higher energy demand could provide additional insights into how demographic and economic factors influence the feasibility of high-renewable penetration. While this study primarily examines the technical feasibility of high-renewable energy integration, a techno-economic analysis was not included in its scope. Future research should incorporate an economic assessment to evaluate the financial feasibility, investment requirements, and potential policy incentives necessary for the practical implementation of the proposed transition pathways.

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51st Ordinary Annual Assembly of the Croatian Academy of Engineering and the 2nd Mini Scientific and Professional Conference

The 51st Ordinary Annual Assembly of the Croatian Academy of Engineering and the 2nd Mini Scientific and Professional Conference "Croatian Academy of Engineering – a Cohesive Factor of Technical and Biotechnical Sciences and the Croatian Economy" took place on June 3, 2024 in the Great Lecture Hall (joint lecture hall) of the Faculty of Food and Biotechnology and the Faculty of Mining, Geology and Petroleum, University of Zagreb. The Assembly was divided into two parts: the working part and the ceremonial part. In the working part, the Assembly of the Academy was informed about the financial status of the Academy and the activities of the Board, the Departments, the Committee, the Centre, the Economic Council, the Scientific Council and the editorial boards of the journal Engineering Power and the Academy's Annual.

The new edition of the Annual for 2023 was presented, in which 20 scientific, professional and review papers by Academy members on the topic of "Environmental Engineering and Circular Economy" were published.

The Assembly was attended by Academy members and distinguished guests from science and industry. The Assembly was welcomed by Mr. Darko Tot (City of Zagreb, City Office for Education, Sports and Youth), Mr. Hrvoje Meštrić (Ministry of Science, Education and Youth of the Republic of Croatia, Directorate for Science and Technology), Academician Sven Lončarić (Croatian Academy of Sciences and Arts) and Mr. Zdravko Jurčec (Croatian Engineering Association).

During the ceremonial part of the Assembly, diplomas were awarded to the new full members and emeritus members and the winners of the Academy Awards 2023 were honored.

The following full members were appointed:

– Prof. Stela Jokić, PhD, Department of Bioprocess Engineering,

– Prof. Jana Žiljak Gršić, PhD, Department of Graphical Engineering,

– Prof. Mirta Barnović, PhD, Department of Information Systems,

– Prof. Mario Dobrilović, PhD, Department of Mining and Metallurgy,

– Prof. Lidija Ćurković, PhD and Prof. Lovre Krstulović-Opara, PhD, Department of Mechanical Engineering and Naval Architecture, and

– Prof. Željko Hocenski, PhD, Department of Systems and Cybernetics.

The following emeritus members were appointed:

– Prof. Andreja Moguš-Milanković, PhD and Prof. Srećko Tomas, PhD, Department of Chemical Engineering and

– Prof. Darko Vrkljan, PhD, Department of Mining and Metallurgy.

The prizes of Croatian Academy of Technical Sciences for the year 2023 were awarded at the Assembly. The Lifetime Achievement Award "The Power of Knowledge" was awarded to Prof. Emerita Ana Marija Grancarić and Prof. Hrvoje Gold, PhD. The annual "Rikard Podhorsky" prize was awarded to Prof. Verica Dragović-Uzelac, PhD, Assoc. Prof. Daniel Hofman, PhD, and Assoc. Prof. Željko Knezić, PhD. The "Vera Johanides" prize for young researchers (for science) was awarded to Marija Habijan, PhD, Nadir Kapetanović, PhD, Deni Kostelac, PhD and Ivana Martić, PhD.

The financial support for HATZ prizes were provided by Xellia d.o.o. Zagreb and CENTER FOR VEHICLES OF CROATIA (CVH), Zagreb.

Immediately before the 51st HATZ Assembly, the 2nd Mini Scientific and Professional Conference "Croatian Academy of Technical Sciences - a Cohesive Factor of Technical and Biotechnical Sciences and Croatian Economy" was held. The lectures were given by the winners of the "Rikard Podhorsky" and "Vera Johanides" awards, which are awarded annually by the Croatian Academy of Technical Sciences for the year 2023. As part of their presentations, the award winners presented an overview of the results of scientific research and professional projects, with a focus on the application of research results in cooperation with industry.

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