Energy 286 (2024) 129478

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

An energy community as a platform for local sector coupling: From complex modelling to simulation and implementation

Edvard Košnjek [a,b], Boris Sučić [a,b,*], Dušan Kostić [c], Tom Smolej [d]

[a] Jozef Stefan Institute, Jamova cesta 39, 1000, Ljubljana, Slovenia
[b] Jozef Stefan International Postgraduate School, Jamova cesta 39, 1000, Ljubljana, Slovenia
[c] Tajfun HIL, d.o.o., Bajči Žilinskog bb, 21000, Novi Sad, Serbia
[d] SIJ ACRONI, d.o.o., Cesta Borisa Kidriča 44, 4270, Jesenice, Slovenia

ARTICLE INFO

Handling Editor: Neven Duic

Keywords:
Energy community
Sector coupling
Sustainable development
Excess heat utilization
Complex process modeling

ABSTRACT

This paper presents the reference architecture of a model for sustainable local planning and sector coupling based on an energy-community framework. The proposed approach includes four building blocks: (1) the data-acquisition building block - local energy consumption, (2) the building block for modelling and calculations - local energy conversions, (3) the building block for connecting the infrastructure status and needs with development plans of the energy-network operators and aggregators, and (4) the decision-support building block for local environmental, spatial and energy planning. The proposed approach was tested in a real industrial environment and a local community. Initial simulation results confirmed that excess heat from the energy-intensive company has the potential to replace the natural gas that is currently used for the production of heat in a local district-heating system. The natural gas savings in the district-heating system would be 3,299,676 Nm^3, as the excess heat could cover as much as 68.4 % of the required heat for the local community. It has also been proven that complex modelling and simulation of a future sustainable solution can contribute to its optimization, understanding, and acceptance by all stakeholders and thereby increase the potential of the project's implementation.

1. Introduction

The recent energy crisis once again confirmed that energy and resource efficiency in combination with renewable energy sources must be the backbone of future sustainable development in any sector. It is clear that reaching climate neutrality by 2050, or even before, will require new approaches. One of these new approaches is the Smart Energy System concept, which represents a scientific shift in paradigms away from single-sector thinking to a coherent energy-system understanding of how to benefit from the integration of all sectors and infrastructures [1]. In the framework of the Smart Energy System concept, sector coupling means decentralized energy solutions and local energy communities that are capable of generating, storing, and using their own energy, thereby reducing the reliance on large, centralized energy systems.

At the implementation level, the social, technical and financial realities of local energy projects require new approaches that will make these local projects interesting for the different stakeholders, from utilities, energy service companies to banks and final users. In this context, Barone et al. [2] presented a novel dynamic simulation model capable of analyzing different system typologies, such as the district-heating system, the district heating-and-cooling system and unidirectional/bidirectional networks. A newly developed tool was used to conduct the complete technical and economic feasibility analyses of third/fourth/fifth generation systems. Lumbreras et al. [3] presented a relatively simple, data-driven model for the characterization and prediction of heating loads in buildings connected to a district-heating network with the capability to optimize the resources for heat generation, deriving in both primary energy and economic savings. According to Billerbeck et al. [4], the most important success factors and challenges of heating-and-cooling planning are good communication and data availability. In the context of climate-friendly development, the transformation to low-temperature district-heating grids is essential for the future use of excess industrial heat and solar power in district-heating systems [5].

Kishimoto et al. [6] proposed an innovative design for the steel

* Corresponding author. Jozef Stefan Institute, Jamova cesta 39, 1000, Ljubljana, Slovenia.
E-mail address: boris.sucic@ijs.si (B. Sučić).

https://doi.org/10.1016/j.energy.2023.129478
Received 14 April 2023; Received in revised form 23 September 2023; Accepted 25 October 2023
Available online 27 October 2023

industry in 2050 based on a collaboration with local communities and confirmed that locally produced, renewable energy can all be consumed within the local area as the steelworks provide a constant demand for any excess power as an alternative to fossil-fuel energy. Community energy projects are widely thought to be associated with positive local impacts, but the research presented by Berka and Creamer [7] revealed how the diversity of community-owned, renewable-energy projects in the United Kingdom inevitably leads to significant differences in the projects' ability to deliver social, environmental and economic impacts. The development of a sustainable energy infrastructure must be long-term and coherently planned, and above all, it must be built thoughtfully within the framework of joint cooperation between all stakeholders. Referring to renewable-energy communities, as equity-enhancing actors in a just transition and contributing to energy justice, this must be done more carefully than is currently the case [8]. The research of Ceglia et al. [9] emphasized that for the successful development of smart-energy communities it is crucial to have a clear legislative and regulatory framework. This framework should facilitate effective management and a multidisciplinary approach that connects the technical conditions with the socio-economic systems inherent in territorial planning, all while ensuring that the energy system remains risk-free [9].

Razmajoo et al. [10] revealed that the transition to smart-energy communities is more complex and requires the creation of an integrated system, linking electricity, heat, and transport systems. In this context, policymakers and energy experts should ensure that the planning system and industry are aligned and mutually informed about the constraints, key drivers, and opportunities [10]. According to Goulden et al. [11], even smart-grid designers must look beyond the technology and recognize that the most effective smart grid will be one in which intelligence is sourced from the users as well as the devices. Local authorities must also proactively enable and support better spatial planning and long-term investment policies for sustainable projects. According to Ref. [12], the challenge is to comprehensively couple the sectors for electricity, industry, buildings, heating, cooling, transport, water, wastewater, waste management, forestry and agriculture for better integration and increased sustainability.

It is very promising that district energy systems are evolving towards smart thermal grids and providing great opportunities for sustainable and flexible heat-energy supply [13]. Research work presented by Edtmayer et al. [14] has confirmed that a 5th-generation district heat-and-cold network has considerable potential for coupling the power-to-heat sector, from balancing the energy market to purchasing the required electricity on the spot market at the most favorable rate. A district energy system has the flexibility to change energy resources to more environmentally friendly version, setting up pollution limits through policies and controlling pollution through the management of the district energy system [15]. Keplinger et al. [16] presented a dynamic model of a novel electric arc furnace's waste-heat recovery and utilization concept, where the associated simulation results confirmed the potential for tapping the usually wasted heat of an electric arc furnace and reducing industry-related CO_2 emissions. Unfortunately, the participation of energy-intensive companies in joint projects with local communities is still relatively weak, even though that excess industrial heat could also lead to considerable reductions in greenhouse-gas emissions in combined-heat-and-power district-heating systems [17]. Fuo et al. [18] proposed and modelled an interesting large-scale industrial waste-heat heating system integrated with seasonal borehole thermal energy storage that showed good potential for use in urban district-heating networks. The use of low-temperature heat sources in district-heating systems, like the excess heat from data centers, metro stations, sewage systems and service sector buildings' cooling systems is gaining attention as a climate-mitigation measure [19]. In the context of excess-heat utilization, it is very important to match the excess-heat recovery technologies with various heat sources at different temperatures based on energy quality, which can improve the efficiency of the entire system [20]. The research work presented by Li et al. [21] confirmed the potential for the use of distant industrial excess heat that is at temperatures even less than 50 °C in the modern district-heating systems.

Abdalla et al. [22] modelled thermal energy sharing in integrated energy communities with micro-thermal networks and concluded that some heating requirements can be covered by the instantaneous sharing between buildings connected in an energy community. Additionally, the research of Li et al. [23] confirmed that multi-energy sharing communities showed the best economic performance, while under the consumption-responsibility scheme, the communities achieved excellent environmental benefits. Cioccolanti et al. [24] proposed an interesting method for evaluating the recovery potential of low-grade waste heat from the energy-intensive pulp-and-paper industry and highlighted that combining energy-intensive industries and district heating can encourage the creation of low-carbon districts. In the research presented by Minuto et al. [25], data-driven retrofit scenarios and different technology mixes (including roof-top photovoltaic, air-source heat pump, battery energy storage, and electric-vehicle chargers) supplying electric and heat have been simulated for a condominium structure of 87 units. However, according to Ref. [26], a realistic assessment of a residential energy community's profitability can be provided by a well-developed estimation model with proper assumptions as well as with a detailed simulation. Popovski et al. [27] revealed that additional policies are required to make RES-based systems competitive from a private economic perspective and that all development activities require the active involvement of the city and a strategic approach to energy planning. Also, Popovski et al. [27] highlighted that from a socio-economic perspective, district heating and cooling with excess heat is the most feasible solution.

In the context of the future development of advanced local energy projects, it is also necessary to highlight the Clean Energy for All Europeans package, which includes the *Directive on common rules for the internal electricity market* [28] and the revised *Renewable Energy Directive* [29], introducing the concept of energy communities, especially as energy-citizen communities and RES communities, into European legislation. The *Directive on common rules for the internal electricity market* includes new rules that allow the active participation of consumers, individually or through energy-citizen communities in all markets, whether in the production, consumption, or sale of energy or when providing flexibility services [29]. The aim of this directive is to enable more effective cooperation of consumers and producers at the local level and a more effective integration into the electricity system. The revised *Renewable Energy Directive* has a similar goal, aiming to strengthen the role of consumers and enable the accelerated implementation of RES projects at the local level [29]. Local sustainable-energy projects, and in particular local energy communities, are at the heart of the Slovenian National Energy and Climate Plan (NECP) [30]. At the implementation level, these projects can foster connections between local inhabitants, network operators (such as those for electricity, natural gas, and district heating), energy-intensive industries, and energy service providers [30].

The research work described in this paper was inspired by the recommendations proposed by Calise et al. [31], where because of the intrinsic complexity of modern energy systems and the large number of different possible configurations, future research should focus on polygeneration systems in order to correctly address their design, optimization and control and to develop efficient decision-support tools for designers, policy makers and end users. One of the fundamental assumptions of this research work is that local energy projects cannot be truly sustainable without a systematic development approach. The following two research questions that arise in this context are.

- How to efficiently model, simulate and compare the feasibility of a comprehensive set of different, complex, local sustainable-energy projects involving various energy vectors?

- How to systematically include all relevant stakeholders in the sustainable planning process and provide a framework for the assessment and decision-making?

A comprehensive literature review revealed that there is a need to properly model and simulate local sustainable-energy projects with the focus on the integration of excess heat from energy intensive industries to local district-heating systems. In this context the creation of a digital twin can be a step forward to comprehensively reflect the actual implementation scenario on the virtual side and provide meaningful feedback to the decision makers [32]. Also, it is vitally important to recognize and properly appreciate the internal and external stakeholders that can influence the energy and environmental performance of envisioned future projects. According to Ref. [33], it is very important that the focus of designers should be on locally available, renewable-energy sources and/or excess-energy sources. This paper presents the reference architecture of a model for sustainable local planning and sector coupling based on an energy-community framework. The case study presented in this research represents the practical application of the proposed concept in a real industrial environment and a local community.

2. Methodology

The proposed reference architecture of the energy-community model for sustainable local planning and sector coupling is presented in Fig. 1. The proposed approach includes four building blocks: (1) the data-acquisition building block - local energy consumption, (2) the building block for modelling and calculations - local energy conversions, (3) the building block for connecting the infrastructure status and needs with the development plans of energy network operators and aggregators, and (4) the decision-support building block for local environmental, spatial and energy planning. The arrows between the components indicate the information and energy flows between the elements and the building blocks. The proposed concept is in line with the main findings and recommendations of [33], where it is stated that the role of the main stakeholders must be properly addressed and that the business case should be visualized from the start of the planning phase.

These four building blocks, along with their internal connections, form the core of the energy-community model. External factors such as EU and national environmental and energy goals, energy-market conditions, EU and national policies and legislation have a significant influence on the overall success of the project. Stakeholders involved in building blocks 1, 2, and 3 must be prepared to share their data like long-term and short-term development plans, market contracts, production, and investment plans. The main result of a well-functioning building block 4 should be a list of well-prepared local energy projects and a list of not possible solutions or projects that are not reaching their set targets. The purpose of these projects is not only to address the goals of the local community but also to contribute to the national, pan-European, and global environmental and climate efforts.

A flowchart of the practical application of the common planning concept is given in Fig. 2. At the beginning of the planning process, the content and limitations of the local sustainable project must be determined, and the geographical boundaries of the project must be defined. Within these boundaries, all the relevant stakeholders must be identified, followed by a review of the available data and development plans in the selected area. The data-acquisition process starts with comprehensive interviews of the identified stakeholders. The result of such inquiries is a complex set of input data used by industry representatives, local communities, and citizens to describe their typical needs and to draft the overall implementation processes related to energy use, energy conversions, and environmental impacts. This must be accompanied by a sensitivity analysis that will help to identify critical factors that can affect the overall feasibility of the energy community. A sensitivity analysis in the context of energy communities provides valuable insights into the robustness of decisions, identifying key risk areas, and ensuring long-term sustainability and success. The final part of the initial planning phase is the identification of the common interests of all the identified stakeholders for the realization of the initially set goals. This is in line with the integrated design process introduced by Ikudayisi et al. [34], which is a concerted and collaborative process that focuses on

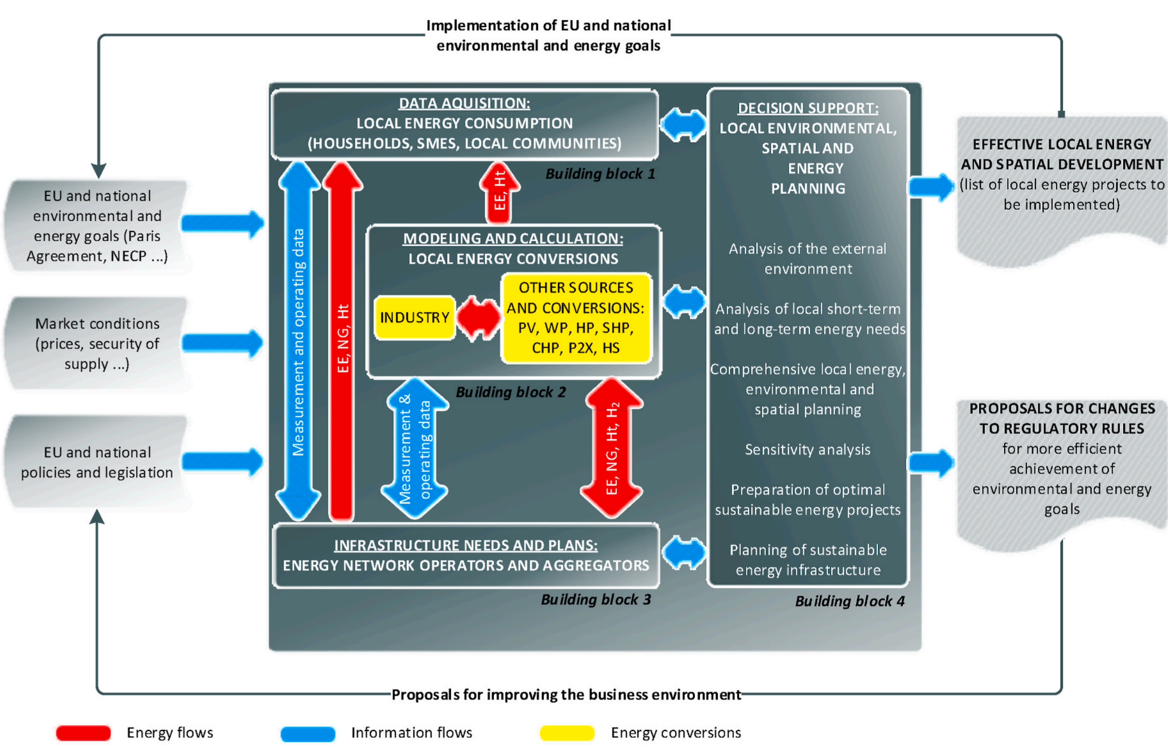

Fig. 1. Proposed reference architecture of an energy-community model for sustainable local planning and sector coupling.

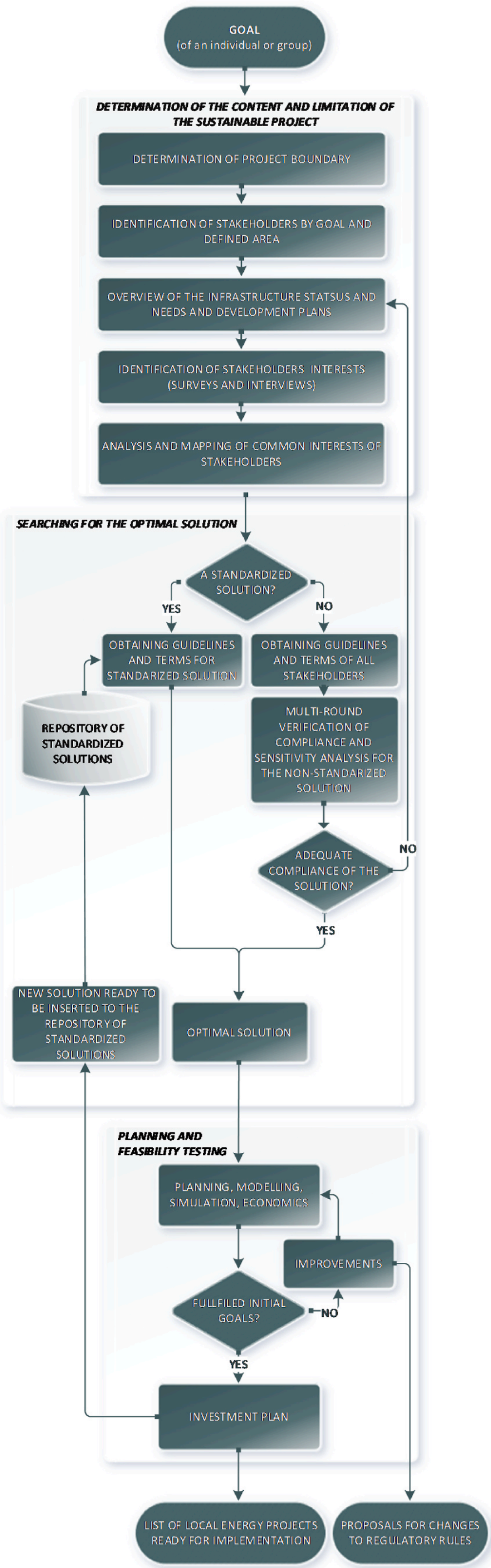

Fig. 2. Sustainable-energy projects and the energy-infrastructure common planning process.

achieving sustainable goals through a proper project definition, design assessment, design detailing, and documentation.

The next segment of the common project planning is the identification of the optimal solution. The development of a model of the future system is necessary to test its feasibility. For less complex projects, such as self-sufficient PV, simple models are sufficient, but for complex systems that include several energy vectors, complex models including digital twins are almost necessary. Initiating the development of a sustainable project is an evolving process that intersects with multiple domains, such as technology, finance, social dynamics, and regulation.

Feasibility testing is one of the most challenging and interesting steps of the common sustainable project-planning process. The procedure for feasibility testing is given in Fig. 3. It consists of six consecutive steps.

In case of excess heat utilization, at the beginning of the sustainable-energy project planning and feasibility testing it is necessary to identify and highlight important processes and energy conversions that will be addressed in the project. It is also necessary to identify all the relevant processes that act as a source or as a sink of energy or material flows as well as the stakeholders that own those processes.

Within the proposed concept, the first step is the integration of energy within the process flow charts, which is the basis for decisions on setting up energy cost centers (ECCs), the core elements of the entire energy model of the future energy community. At the conceptual level, the approach based on ECCs clearly belongs to the process-integration family [35]. Due to its simplicity and the results obtained in many industrial applications around the world, a pinch analysis is the most widely used process-integration methodology [12,36]. According to Ref. [35], an ECC can be any department, section or machine that uses a significant amount of energy or creates significant environmental impacts. With the structure of the ECC, designers can schematically present material and energy flows through the addressed production process, their basic transformations and input/output connections with the environment. The structure of the ECC model is defined by the collection of signals in each segment of the plant. ECC-based process modeling and integration are commonly used to improve production control, flexibility research, and record the current operating conditions [35].

The second step is transforming the ECC scheme into a block diagram of the future system. A block diagram is a schematic representation of recorded energy sources and sinks, all the relevant energy conversions, and the physical connections between them. This schematic already indicates the scope and structure of the future system.

In the third step, a system model is created. In the case of the sector-coupling model, designers are dealing with a very complex, multivariable system. Every small component of such a complex system is a nonlinear and time-varying subsystem, which makes it practically impossible to use mathematical-analytical procedures. A complex real system should, therefore, be presented in the form of a model that can be used to run simulations based on historical measurement data. The modeling must be based on the principle of modularity. In the case of very complex real-world systems, it is especially important to determine a sufficiently narrow purpose for the model, which will enable all expectations to be met and at the same time be easy enough to implement. The whole system model should be built in the form of a transfer-functions block diagram.

The fourth step is necessary in the case of a complex system model. To perform real-time emulations, the model developed in a PC-based environment must be transferred to a dedicated computer platform. The use of dedicated computer platforms enables the faster execution of emulations and simulations, and it is also more suitable for the implementation of automated optimization algorithms.

The fifth step is to run the emulations and simulations on a PC or on a dedicated computing platform. A year-long profile of historical data should be used because all the typical operating conditions in production during one year and the seasonal modes of operation are covered and properly addressed.

The final (sixth) step involves the utilization of the simulation results

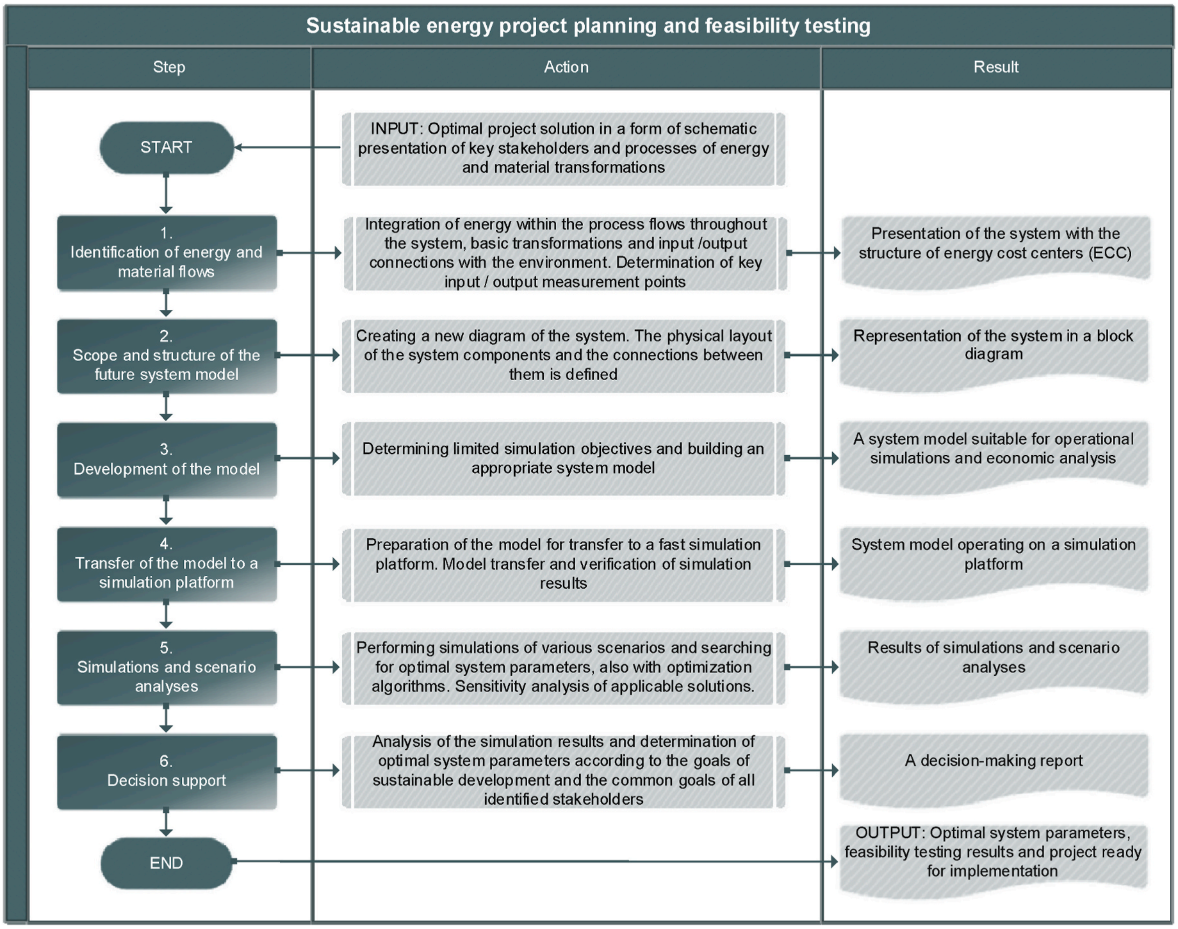

Fig. 3. Sustainable-energy project planning and feasibility testing.

from various system configurations to determine the optimal system parameters that align with the sustainable-development goals and common stakeholder objectives. It also includes sensitivity analysis of applicable solutions. Based on these findings, a decision-making report is prepared, outlining the proposed scope and priorities of the necessary investments for the sustainable-energy project.

2.1. Case study: Sector coupling between an energy-intensive industry and a district-heating system from Slovenia

Research efforts have been dedicated to energy-efficiency improvements in energy-intensive industries. Steel production is one of the most energy-intensive processes in industry [37]. However, it should be considered that even public institutions have a significant role in defining the external context and future development challenges for the steel industry, both in overseeing the development of new standards and in driving demand through investments in public infrastructure and construction [38].

At the time of writing, the concept described is being tested via a prototype version in a major steel producer in Slovenia. The steel plant and local district-heating operator have provided a real testing environment and all the necessary data for the validation of the proposed concept. In terms of energy use and environmental impacts, this steel plant is among the most advanced plants in Europe. The goal of the research was to test whether the proposed concept, enriched with data from the district-heating operator, can be used in a future upgrade of the existing district-heating system and as a decision-support tool for the factory regarding a future upgrade of the production process. According to Ref. [39], this represents an opportunity with unusual levels of research access.

The need for competitiveness on the market is forcing steel plants around the world to systematically and continuously analyze all the possibilities for the optimization of production activities and related cost reduction. According to Ref. [40], the considered steel plant is successful in the field of CO_2-emissions reduction with only 373 kg of CO_2 per ton of steel products in 2021. This achievement was reached through measures that improved operational energy efficiency and the employment of the best available technologies. However, there are still opportunities to reduce the use of natural gas and electricity by utilizing the excess heat from the production process. Part of the excess heat could be used in the district-heating system of a nearby local community. The addressed local community is in the immediate vicinity of the steel plant and has 13,255 inhabitants (2013 census). The majority of the residential and commercial buildings use a gas-powered district-heating system for heating and the preparation of domestic hot water.

3. Results

At the very beginning of the research work, an extensive set of interviews was conducted with selected representatives of the addressed industrial company, local authorities, network operators, and citizens' representatives. In the process of sustainable project planning, the use of all the energy sources, including electricity, natural gas, heat, and hydrogen, was analyzed. However, the main goal of the presented research was to analyze the potential to use excess heat from the energy-intensive production plant in a district-heating system. From the district-heating system's operator's point of view, there are also other options for the future upgrade of the existing district-heating system. The current district-heating system is mainly based on natural-gas-fired cogeneration units that could be replaced by biomass-fired cogeneration units or heat pumps. However, from the perspective of energy efficiency, which is the first principle of the Slovenian NECP, the utilization of industrial excess heat is the highest priority and must be considered whenever it is economically justifiable. In order to support this kind of sector coupling, Slovenian NECP [30] provides a comprehensive set of policy instruments and initiatives that should support agreements between energy-intensive industries and district-heating providers. In this context the investments in the district-heating network will be supported by state initiatives. Unfortunately, under the current energy-policy framework, energy-intensive industries will have to justify the necessary investments in terms of the additional revenue from the selling the excess heat, which can be a significant obstacle to a large-scale implementation. However, it is promising that the first excess-heat-utilization project implemented in Slovenia was the result of a direct cooperation of the district-heating system's operator and the energy-intensive industry without any additional support or subsidy from the state or local municipality [41].

Based on the collected information, a schematic representation of the envisioned sustainable-energy project, including key stakeholders and the processes of energy and material transformations crucial for project planning, was created. The created scheme represents the desired final situation and is shown in Fig. 4. The connections and technological assemblies that have not yet been installed on-site are shown with a surrounding glow. Since the production of excess heat might not always align with the demand in the district-heating system, heat storage has to be added in the system.

In the next step, the initial scheme was transformed into the structure of ECCs. The new scheme includes ECCs that are identified as potential candidates for the partial or complete replacement of energy sources with excess heat. In Fig. 5 they are marked with a brown dashed line. ECC6 to ECC14 are systems that provide heat in various forms (hot water, steam) for a production process (ECC17). This heat can be partially or completely replaced by the excess heat obtained in the added ECC15, which is a set of devices (heat exchangers) and systems for excess-heat recovery. Excess-heat sources that are tackled in this analysis are capable of providing high-temperature heat in the form of hot water and steam. This excess heat can be returned to the production process and/or injected into the district-heating system (ECC16). The injected high-temperature excess heat into the local district-heating system has the potential to partially replace the natural gas currently used for heat production, providing energy, environmental, and cost benefits to the operator and all the consumers. The share of low-temperature excess heat in the overall balance of utilized excess heat is approximately 6 % and it is assumed that this will be utilized within the addressed steel factory. The new scheme also includes excess-heat sources as part of the production process (ECC17), which are represented as Energy Cost Units (ECU 17.1 to ECU 17.6).

Based on the ECC structure (Excess Heat Utilization Boundary in Fig. 5), a schematic of the connections between the sources and sinks of excess heat was created. The scope and structure of the excess-heat-utilization system model are shown in Fig. 6.

In the presented case, it was very important to investigate the time alignment of the individual potential sources and sinks, considering the available power, the spatial distribution of sources and sinks, as well as the availability of the already-built infrastructure.

3.1. *Initial results of excess-heat-utilization model and simulation-speed enhancement*

The complete model of excess-heat utilization was developed in the MATLAB environment and consists of 31 first-order delay and dead-time transfer functions (FODT), 2 first-order delay transfer functions (FO), 8

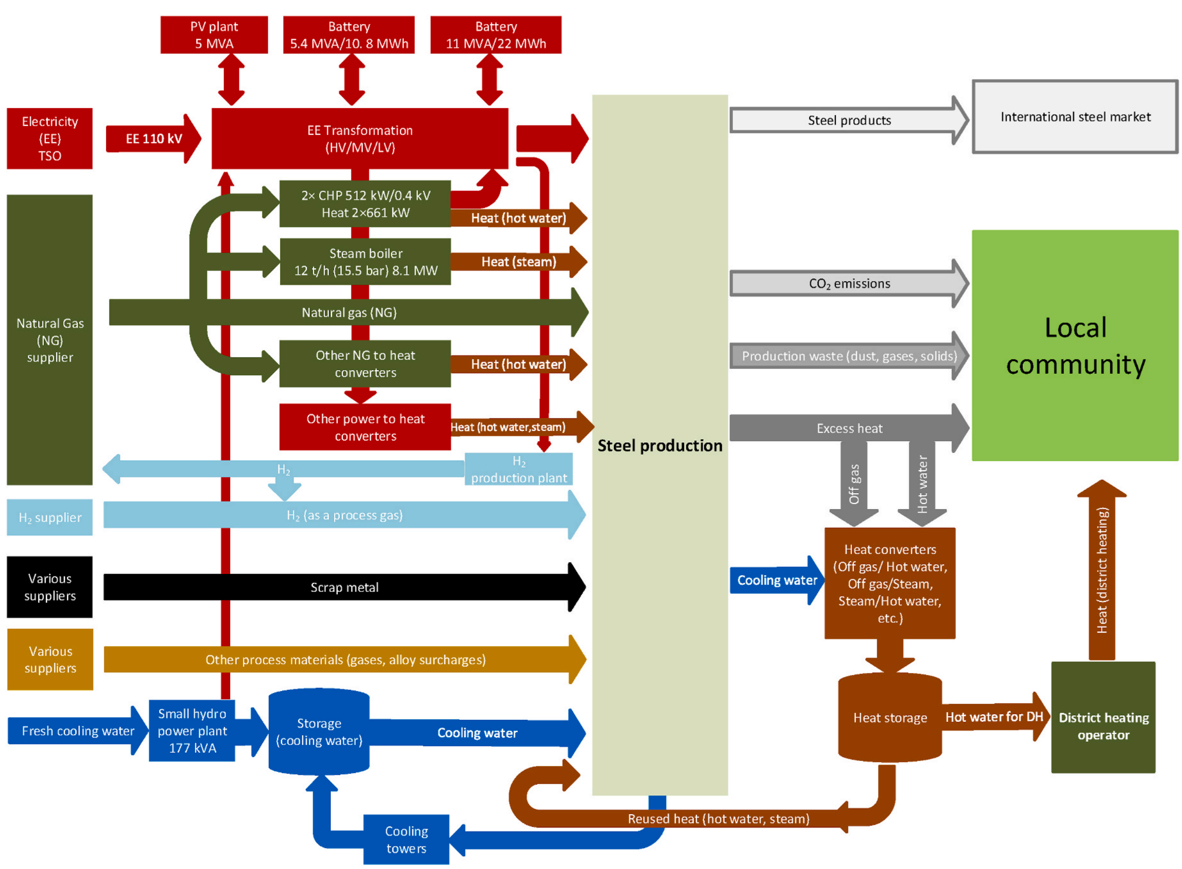

Fig. 4. Schematic of the sustainable-energy project.

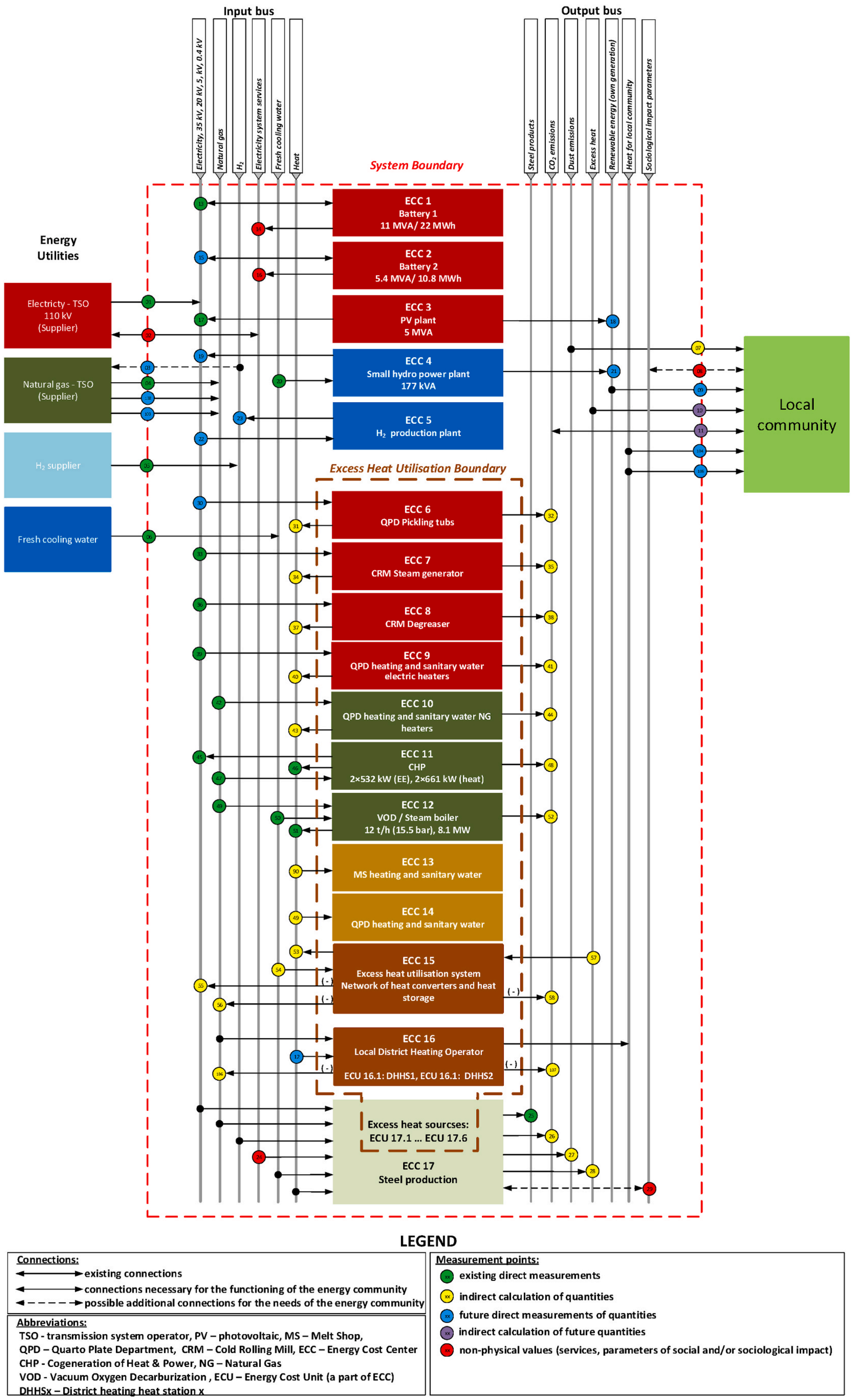

Fig. 5. Material and energy flows through the ECC structure.

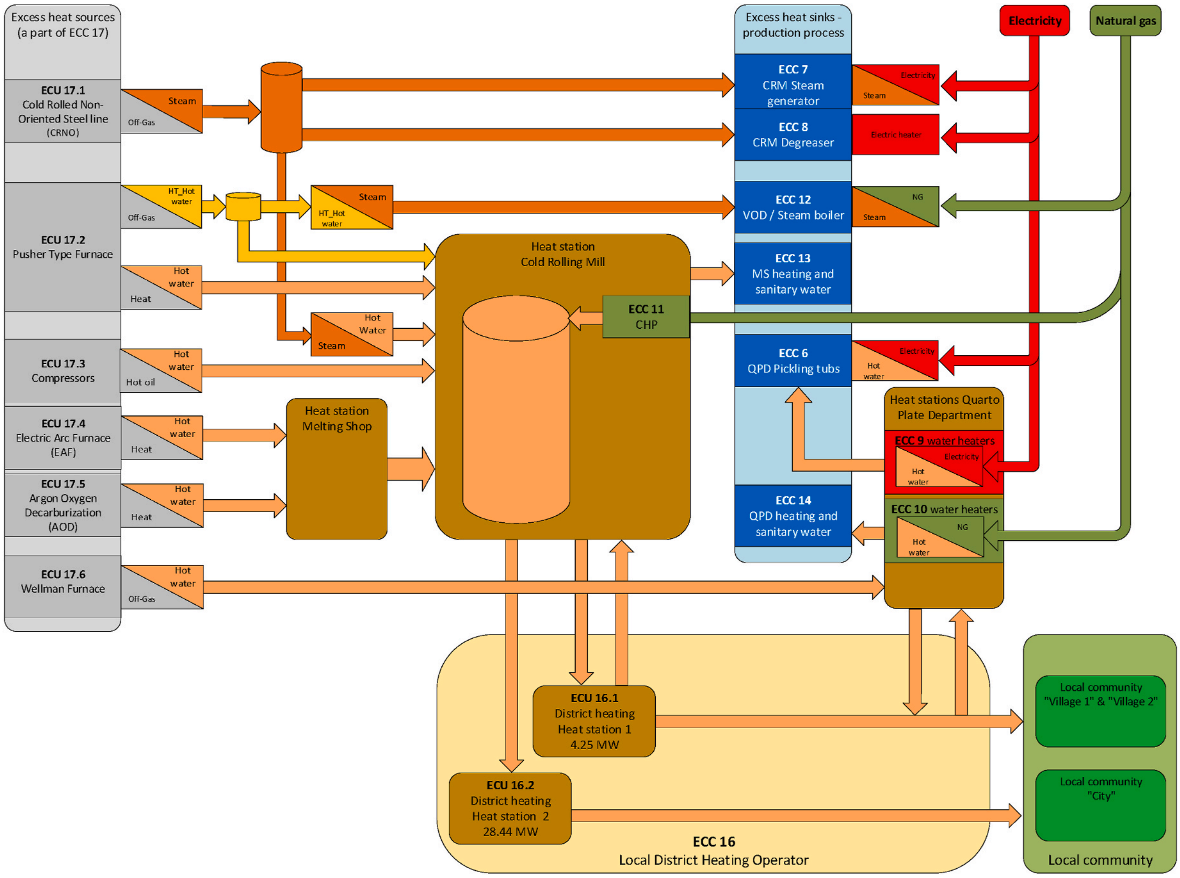

Fig. 6. Schematic of the excess-heat utilization within the project.

storages, 33 two-position controllers, 22 measurement inputs (15-min data), and 236 adjustable parameters.

To enhance the speed of the simulation, a model developed for the PC platform was transferred to a dedicated computer platform consisting of specially designed hardware-in-the-loop devices capable of emulating high-fidelity models used for the design, testing, and validation of various technologies. At the core of this technology are ultra-low latency application-specific processors, together with an optimized software architecture based on proprietary numerical algorithms. Due to their unique hardware architecture, the devices of this platform are able to simulate a high-fidelity, low-latency simulation with the simulation step down to 200 ns, and they can be interfaced with other devices using fast sampling I/O or a wide range of different communication protocols. The simulation results of the transferred model were compared with the results of the PC platform-based simulation, with the observed difference being less than 0.5 %.

The results for the simulation of the selected combinations of excess-heat sources and sinks (so-called utilization scenarios) are given in Table 1. The developed model allows the designer and decision-maker to choose which sources and sinks are included in the simulation process via the dashboard switches. In Table 1, the results of the selected combination of sources and sinks (columns 2 and 3) are presented, where the excluded elements are crossed out. The results of the simulations clearly show the influence of an individual source or sink or their combination on the final result. In this way, the designer and decision-maker gain important information for deciding on the priorities of investing in the excess-heat utilization system. The developed model also enables an evaluation of the sustainable-development goals (energy efficiency, CO_2 emissions reduction), evaluation of energy savings, and revenue streams from the heat that is sold. In this case the designer or decision-maker only has to enter the prices of the selected energy sources that are necessary for the analysis of the economic viability of each utilization scenario. The model also makes it possible to change the capacity of the heat storages located in the nodes of the system. Due to the highly variable availability of the sources and the dynamics of the sinks, it is possible to use more excess heat by increasing the storage capacity, but it has to be aware that this also increases the overall costs in the excess-heat-recovery system. In addition to the capacity of the storage tanks, the power of the heat exchangers, the dimensions and properties of the connecting pipelines, etc., also have a significant effect on the use of excess heat, all of which can be easily changed with the model parameters.

The time alignment for heat consumption in the local community and the transfer of the available excess heat between the source (ECC 15) and the sink, district-heating system "Village 1 & 2," is shown in Fig. 7. This alignment is also presented in the load-duration diagram (Fig. 8), which shows that excess heat can cover 92.4 % of the heating needs of the local community throughout the year. The current district-heating system for "Village 1 & 2″ does not provide domestic hot water and that is the reason why it has around 5900 operating hours per year. Similarly, Figs. 9 and 10 illustrate the conditions for the excess-heat utilization in the "City" district-heating system. In the case of the "City" district-heating system, excess heat can cover 65.6 % of the heating needs throughout the year. In order to increase the share of excess heat in the "City" district-heating system, low-temperature excess heat sources should be tackled too. Utilizing the low-temperature excess heat would allow for almost 100 % coverage of the heating needs from hour 3300. However, this would necessitate the installation of additional heat pumps, and due to the high and volatile electricity prices, this cannot be economically justified at the moment.

The results are a clear indication of how currently unused excess heat can be utilized to create a complex energy community that will enable

Table 1
Results of simulation for excess heat utilization – utilization scenarios.

No	Excess heat sources	Excess heat sinks	Excess heat used in		Steel production savings			District-heating savings		Total savings		
			production [MWh]	district heating [MWh]	EE [MWh]	NG [Nm^3]	CO_2 [t]	NG [Nm^3]	CO_2 [t]	EE [MWh]	NG [Nm^3]	CO_2 [t]
1	ECU 17.1 ECU 17.2 ECU 17.3 ECU 17.4 ECU 17.5 ECU 17.6 ECC 11	ECC 6 ECC7 ECC 8 ECC 9 ECC 10 ECC 12 ECC 13 ECU 16.1 ECU 16.2	11,440	31,372	1684	817,174	2103	3,299,676	6111	1684	4,116,850	8214
2	ECU 17.1 ECU 17.2 ECU 17.3 ECU 17.4 ECU 17.6 ECC 11	ECC 6 ECC7 ECC 8 ECC 9 ECC 10 ECC 12 ECC 13 ECU 16.1 ECU 16.2	11,486	30,621	1684	817,174	2103	3,220,687	5965	1684	4,037,861	8068
3	ECU 17.1 ECU 17.2 ECU 17.3 ECU 17.4 ECU 17.5 ECC 11	ECC7 ECC 8 ECC 12 ECC 13 ECU 16.1 ECU 16.2	10,198	30,527	833	769,258	1716	3,210,800	5947	833	3,980,058	7663
4	ECU 17.1 ECU 17.2 ECU 17.3 ECU 17.4 ECU 17.5 ECU 17.6 ECC 11	ECC 6 ECC7 ECC 8 ECC 9 ECC 10 ECC 12 ECC 13	11,486	−67	1684	817,174	2103	−7047	−13	1684	810,127	2090
5	ECU 17.1 ECU 17.2 ECU 17.3 ECU 17.4 ECU 17.5 ECU 17.6 ECC 11	ECC 6 ECC7 ECC 8 ECC 9 ECC 10 ECC 12 ECC 13 ECU 16.1	11,486	3249	1684	817,174	2103	341,727	633	1684	1,158,901	2736
6	ECU 17.1 ECU 17.2 ECU 17.3 ECU 17.6 ECC 11	ECC 6 ECC7 ECC 8 ECC 9 ECC 10 ECC 12 ECC 13 ECU 16.1 ECU 16.2	11,486	21,316	1684	817,174	2103	2,241,996	4153	1684	3,059,170	6256

the green transition of an energy-intensive industrial company and a district-heating company through sector coupling. In this context, the natural gas savings in the district-heating system would be 3,299,676 Nm^3, as the excess heat could cover as much as 68.4 % of the required heat for the local community. Additionally, the proposed concept allows decision makers to evaluate the achievement of specific development goals to determine the optimal investment volume for utilizing individual sources of excess heat and prioritize these investments. Any sources and sinks that do not meet set development goals and economic criteria can be easily excluded from further consideration.

4. Discussion

The ambition of the presented research work was to show, theoretically and on a practical example, how it is possible to systematically promote the cooperation of relevant stakeholders in the local environment and to improve the processes of preparing feasible energy projects for the optimal achievement of sustainable development goals. Valuable lessons regarding the effective modeling, simulation, and feasibility testing of complex local sustainable-energy projects that include different energy vectors have been learned. At the level of an individual project, it has been confirmed that the effective modeling of complex systems and the development of a digital twin for performing the simulations is a very important step in the feasibility-testing process.

A practical application of the developed model confirmed that good communication and data availability are the most important success factors and challenges for heating-and-cooling planning, which is in line with the findings of Billerbeck et al. [4]. In the addressed case study, the key stakeholders admitted that they are aware of the need for coordinated action and that it would be rational to address common national energy and climate challenges together. The review of the Slovenian NECP also showed the need for a more comprehensive approach, both in

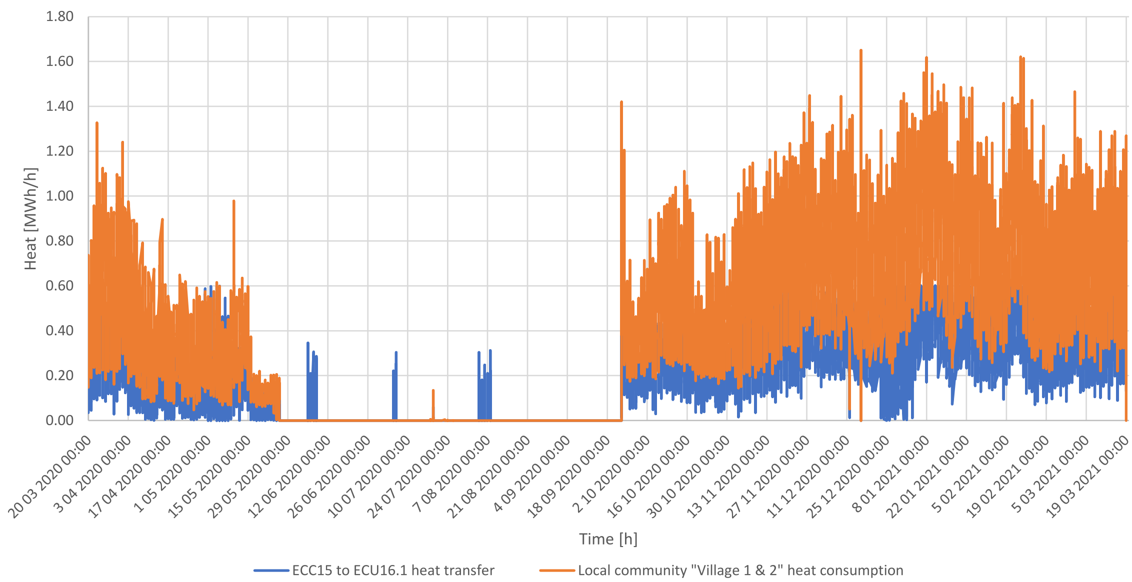

Fig. 7. Excess heat utilization in "Village 1 & 2″ district-heating system.

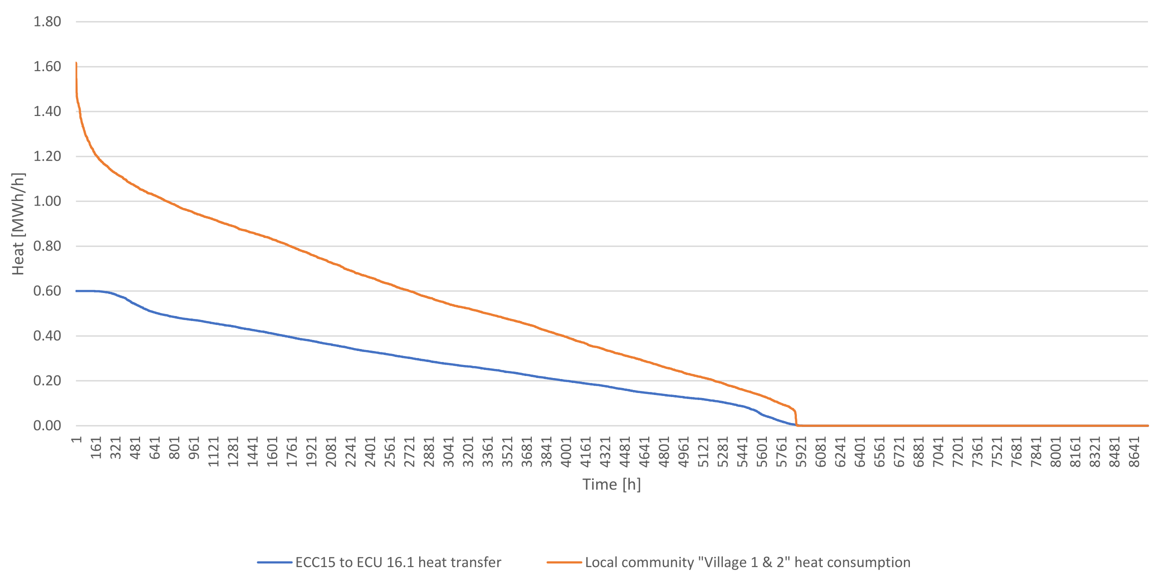

Fig. 8. Load duration diagram of excess-heat utilization in "Village 1 & 2″ district-heating system.

the long-term planning of the energy infrastructure and in the optimal planning of energy projects, which is also in line with the findings reported by Ceglia et al. [9].

A special challenge was the modeling of non-existing systems for excess-heat utilization. The model parameters cannot be determined without the close cooperation of experts working in the production process. However, as their understanding of system theory is often limited, the proposed use of simple transfer functions whose parameters can be easily explained (time required to warm up the system after switching on, expected losses, conversion factors, and dead time) has proven to be a decisive advantage. In this context, the findings of Goulden et al. [11] were very useful since, in the initial design phase, the initiators and developers of innovative projects have to look beyond the particular technologies. During the testing phase, it was found that the proposed methodology and the developed model play a key role in a better understanding of the functioning of the entire system. The results of the proposed approach contributed to the ambition of utilizing the potential of excess heat from the production process in the industrial plant and in the local community. Also, the results confirmed the potential for utilizing the excess heat in modern district-heating systems that have been also reported by Li et al. [21].

When it comes to the replicability, it has to be admitted that the proposed approach requires a huge amount of reliable data from various sources and stakeholders. This is considered as a big obstacle for implementation in countries with a lack of available data. Also, many industrial companies are still reluctant to share their data, which means that appropriate incentives at the local level should be proposed for companies that support sustainable practices, such as tax breaks or subsidies. On the other hand, sharing data and supporting green initiatives can boost shareholder confidence and potentially enhance the stock value of energy intensive industrial company.

The conducted research work also revealed that there are additional

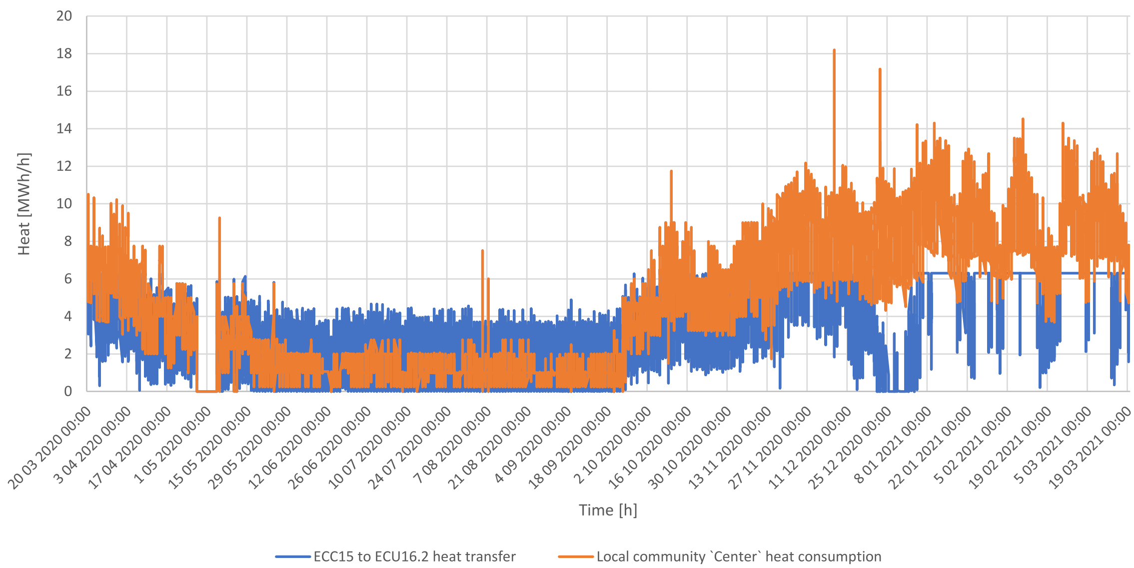

Fig. 9. Excess-heat utilization in "City" district-heating system.

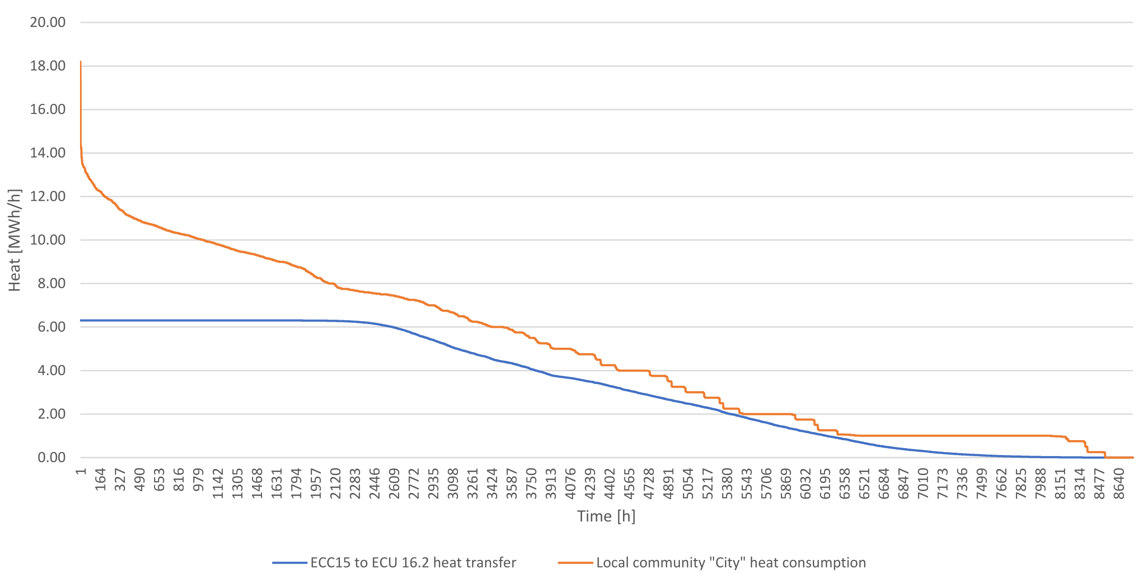

Fig. 10. Load duration diagram of excess-heat utilization in "City" district-heating system.

challenges that must be addressed in the context of future exploitation of the industrial excess heat in the local district-heating systems. During the data-collection process it was noticed that agreements between representatives of the energy-intensive industry and the district-heating providers can be complex, considering factors like heat pricing, supply reliability, and liabilities. Also, comprehensive modelling of the addressed systems, industrial and district heating, confirmed that integration of industrial processes with district-heating systems requires modifications to both systems, which can be technically challenging and can increase the costs of the proposed solution and extend the payback period. The added complexity of integrating two systems can also lead to increased maintenance needs. An analysis of the available historical data confirmed that coordinating the operations of the industry and the district-heating system to ensure a continuous supply can be challenging, especially when unforeseen shutdowns or reductions in industrial activity occur. Despite these challenges, the presented research clearly confirmed that the benefits of utilizing industrial excess heat in district-heating systems are considerable, making it well worth exploring. This is also in line with findings from Popovski et al. [27]. In order to make it interesting for the investors, district heating with excess heat requires better integration technologies, supportive regulations, and public-awareness campaigns that will clearly explain all the benefits [27].

From the perspective of the district-heating company, it is clear that there is a need to have reserve sources of heat in cases when for various reasons excess heat is not available. The research also revealed that there are situations when the production of excess heat does not align with the demand in the district-heating system. This also leads to higher costs due to the need for additional storage capacities and auxiliary systems. On the other hand, since the operational costs are low, exploitation of the excess heat in the district-heating system reduces the influence of the volatile energy prices on the final price of the delivered heat to the consumers.

In very complex, real-world systems, the gradual development of the model was especially important. In the context of future upgrades, the structure of the described model will remain the same, and future research will be focused on finding sufficiently detailed modeling elements that will enable more detailed modeling, while maintaining the complexity of the model at a reasonable level. Due to the modularity of the proposed reference architecture, the excess heat-utilization model can be linked to the future electricity-simulation model that will be used for the simulation of the behavior of battery energy-storage systems, PV plants, and combined heat-and-power systems. This will enable the creation of a complete model of the sustainable-energy community project with online data from the production plant and the district-heating system. This model will also represent a digital twin of the future sustainable-energy system.

5. Conclusion

The results of the addressed case study clearly show that if all the analyzed sources of excess heat from the production process were to be utilized, significant energy savings and CO_2-emissions reduction can be achieved. Also, the research once again revealed that the main challenge in planning a sustainable-energy project is the appropriate involvement of all the relevant stakeholders in the planning process. In this context, the proposed reference architecture of an energy-community model for sustainable local planning and sector coupling can be considered as a promising solution for bridging existing communication and implementation gaps. Instead of addressing the decarbonization of each sector in isolation, the proposed reference architecture offers a comprehensive and system-wide approach that ensures that progress in one sector (the energy-intensive industry) can support and amplify progress in other (district heating).

The proposed modeling concept allows a detailed evaluation of available heat sources within each ECC. On the implementation level, ECC-based modelling, supported by a detailed data flow, empowers the energy-system designers with the authority to propose new solutions if they believe that they can contribute to the better use of resources and energy at the level of an energy community. However, a particularly large challenge is how to effectively follow the goals of sustainable development and establish a mechanism for continuous improvements throughout the entire lifecycle of sustainable-energy solutions. Therefore, in the framework of future research, it will be necessary to develop a system for measuring the integrity of a sustainable, local, energy-infrastructure plan.

CRediT authorship contribution statement

Edvard Košnjek: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Boris Sučić:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Dušan Kostić:** Investigation, Visualization, Software, Writing – original draft. **Tom Smolej:** Formal analysis, Data curation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors would like to thank the European Commission and the partners of the European Union's Horizon 2020 research and innovation programme project "CREATORS - CREATing cOmmunity eneRgy Systems" (https://cordis.europa.eu/project/id/957815) for their support.

References

[1] Lund H. Renewable energy systems - a smart energy systems approach to the choice and modeling of 100% renewable solutions. second ed. Academic Press; 2014.

[2] Barone G, Buonomano A, Forzano C, Palombo A. A novel dynamic simulation model for the thermo-economic analysis and optimisation of district heating systems. Energy Convers Manag 2020;220. https://doi.org/10.1016/j.enconman.2020.113052.

[3] Lumbreras M, Garay-Martinez R, Arregi B, Martin-Escudero K, Diarce G, Raud M, Hagu I. Data driven model for heat load prediction in buildings connected to District Heating by using smart heat meters. Energy 2022;239. https://doi.org/10.1016/j.energy.2021.122318. part D).

[4] Billerbeck A, Fritz M, Aydemir A, Manz P. Strategic heating and cooling planning to shape our future cities, European council for an energy-efficient economy (ECEEE summer study) – panel 5. Towards sustainable and resilient communities. ECEEE Summer Study Proceedings 2022:601–11.

[5] Lund H, Duic N, Østergaard PA, Vad Mathiesen B. Future district heating systems and technologies: on the role of smart energy systems and 4th generation district heating. Energy 2018;165:614–9. https://doi.org/10.1016/j.energy.2018.09.115.

[6] Kishimoto A, McLellan BC, Tezuka T. Conceptual design of the steel industry in 2050 considering collaboration with local communities. Energy Convers Manag X 2022;15. https://doi.org/10.1016/j.ecmx.2022.100251.

[7] Berka AL, Creamer E. Taking stock of the local impacts of community owned renewable energy: a review and research agenda. Renew Sustain Energy Rev 2018; 82(3):3400–19. https://doi.org/10.1016/j.rser.2017.10.050.

[8] Hanke F, Guyet R, Feenstra M. Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases. Energy Res Social Sci 2021;80. https://doi.org/10.1016/j.erss.2021.102244.

[9] Ceglia F, Esposito P, Marrasso E, Sasso M. From smart energy community to smart energy municipalities: literature review, agendas and pathways. J Clean Prod 2020;254. https://doi.org/10.1016/j.jclepro.2020.120118.

[10] Razmjoo A, Mirjalili S, Aliehyaei M, Østergaard PA, Ahmadi A, Nezhad MM. Development of smart energy systems for communities: technologies, policies and applications. Energy 2022;248. https://doi.org/10.1016/j.energy.2022.123540.

[11] Goulden M, Bedwell B, Rennick-Egglestone S, Rodden T, Spence A. Smart grids, smart users? The role of the user in demand side management. Energy Res Social Sci 2014;2:21–9. https://doi.org/10.1016/j.erss.2014.04.008.

[12] Mikulčić H, Baleta J, Klemeš JJ, Wang X. Energy transition and the role of system integration of the energy, water and environmental systems. J Clean Prod 2021; 292. https://doi.org/10.1016/j.jclepro.2021.126027.

[13] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, Vad Mathiesen B. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[14] Edtmayer H, Nageler P, Heimrath R, Mach T, Hochenauer C. Investigation on sector coupling potentials of a 5th generation district heating and cooling network. Energy 2021;230. https://doi.org/10.1016/j.energy.2021.120836.

[15] Lake A, Rezaie B, Beyerlein S. Review of district heating and cooling systems for a sustainable future. Renew Sustain Energy Rev 2017;67:417–25. https://doi.org/10.1016/j.rser.2016.09.061.

[16] Keplinger T, Haider M, Steinparzer T, Patrejko A, Trunner P, Haselgrübler M. Dynamic simulation of an electric arc furnace waste heat recovery system for steam production. Appl Therm Eng 2018;135:188–96. https://doi.org/10.1016/j.applthermaleng.2018.02.060.

[17] Ivner J, Broberg Viklund S. Effect of the use of industrial excess heat in district heating on greenhouse gas emissions: a systems perspective. Resour Conserv Recycl 2015;100:81–7. https://doi.org/10.1016/j.resconrec.2015.04.010.

[18] Guo F, Zhu X, Li P, Yang X. Low-grade industrial waste heat utilization in urban district heating: simulation-based performance assessment of a seasonal thermal energy storage system. Energy 2022;239. https://doi.org/10.1016/j.energy.2021.122345.

[19] Sandvall A, Hagberg M, Lygnerud K. Modelling of urban excess heat use in district heating systems. Energy Strategy Rev 2021;33. https://doi.org/10.1016/j.esr.2020.100594.

[20] Wang X, Tian H, Yan F, Feng W, Wang R, Pan J. Optimization of a distributed energy system with multiple waste heat sources and heat storage of different temperatures based on the energy quality. Appl Therm Eng 2020;181. https://doi.org/10.1016/j.applthermaleng.2020.115975.

[21] Li Y, Xia J, Su Y, Jiang Y. Systematic optimization for the utilization of low-temperature industrial excess heat for district heating. Energy 2018;144:984–91. https://doi.org/10.1016/j.energy.2017.12.048.

[22] Abdalla A, Mohamed S, Bucking S, Cotton JS. Modeling of thermal energy sharing in integrated energy communities with micro-thermal networks. Energy Build 2021;248. https://doi.org/10.1016/j.enbuild.2021.111170.

[23] Li L, Zhang S, Cao X, Zhang Y. Assessing economic and environmental performance of multi-energy sharing communities considering different carbon emission responsibilities under carbon tax policy. J Clean Prod 2021;328. https://doi.org/10.1016/j.jclepro.2021.129466.

[24] Cioccolanti L, Renzi M, Comodi G, Rossi M. District heating potential in the case of low-grade waste heat recovery from energy intensive industries. Appl Therm Eng 2021;191. https://doi.org/10.1016/j.applthermaleng.2021.116851.

[25] Minuto FD, Lazzeroni P, Borchiellini R, Olivero S, Bottaccioli L, Lanzini A. Modeling technology retrofit scenarios for the conversion of condominium into an energy community: an Italian case study. J Clean Prod 2021;282. https://doi.org/10.1016/j.jclepro.2020.124536.

[26] Fina B, Monsberger C, Auer H. Simulation or estimation?—two approaches to calculate financial benefits of energy communities. J Clean Prod 2022;330. https://doi.org/10.1016/j.jclepro.2021.129733.

[27] Popovski E, Fleiter T, Santos H, Leal V, Oliveira Fernandes E. Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities-A case study for Matosinhos. Portugal, Energy 2018;153: 311–23. https://doi.org/10.1016/j.energy.2018.04.036.

[28] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast), Official Journal of the European Union 2018, L 328; 82-209, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC (last accessed: August 30 2023).

[29] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast), Official Journal of the European Union 2019, L 158; 125-199, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2019.158.01.0125.01.ENG&toc=OJ:L:2019:158:TOC (last accessed: August 30 2023).

[30] Integral national energy and climate plan of the Republic of Slovenia, Ministry of Infrastructure, Ljubljana, 2020, available at: https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/nepn/dokumenti/nepn_5.0_final_feb-2020.pdf (last accessed: August 12 2022).

[31] Calise F, de Notaristefani di Vastogirardi G, Dentice d'Accadia M, Vicidomini Maria. Simulation of polygeneration systems. Energy 2018;163: 290–337. https://doi.org/10.1016/j.energy.2018.08.052.

[32] Ren J, Zhou T, Rong Y, Ma Y, Ahmad R. Feature-based modeling for industrial processes in the context of digital twins: a case study of HVOF process. Adv Eng Inf 2022;51. https://doi.org/10.1016/j.aei.2021.101486.

[33] Verstraten P, Niessink R, Duedahl M, Verheij F, Huygen A A. Best practices for planning and construction of thermal networks identified in the EU. ISBN 978-92-76-44396-4 (online). Publications Office of the European Union; 2021. available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC126954. [Accessed 30 August 2023].

[34] Ikudayisi AE, Chan APC, Darko A, Adegun OB. Integrated design process of green building projects: a review towards assessment metrics and conceptual framework. J Build Eng 2022;50. https://doi.org/10.1016/j.jobe.2022.104180.

[35] Morvay ZK, Gvozdenac DD. Applied industrial energy and environmental management. Chichester, United Kingdom: John Wiley & Sons; 2008.

[36] Klemeš JJ, Lam HL. Process integration for energy saving and pollution reduction. Energy 2011;36(8):4586–7. https://doi.org/10.1016/j.energy.2011.05.025.

[37] The International Energy Agency (IEA). World energy outlook 2021. Paris: IEA/OECD; 2021.

[38] Rootzén J, Johnsson F. CO_2 emissions abatement in the Nordic carbon-intensive industry – an end-game in sight? Energy 2015;80:715–30. https://doi.org/10.1016/j.energy.2014.12.029.

[39] Eisenhardt KM, Graebner ME. Theory building from cases: opportunities and challenges. Acad Manag J 2007;50(1):25–32. https://doi.org/10.5465/AMJ.2007.24160888.

[40] The International Energy Agency (IEA). Iron and steel technology Roadmap: towards more sustainable steelmaking. IEA Publications; 2020. available at: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf. [Accessed 15 February 2023].

[41] Malinauskaite J, Jouhara H, Egilegor B, Al-Mansour F, Ahmad L, Pusnik M. Energy efficiency in the industrial sector in the EU, Slovenia, and Spain. Energy 2020;208. https://doi.org/10.1016/j.energy.2020.118398.