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Principles of Building Digital Twins to Design Integrated Energy Systems

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Abstract: The design of integrated energy systems (IESs) is a challenging task by reason of the highly complex configurations of these systems, the wide range of equipment used, and a diverse set of mathematical models and dedicated software employed to model it. The use of digital twins allows modeling in virtual space for various IES configurations. As a result, an optimal option of IES is obtained, which is implemented in the construction or expansion of a real-world IES. The paper proposes the principles of building digital twins for solving the IES design problems. The paper presents a new methodological approach developed by the authors to design an IES with the help of its digital twin. This approach includes the following components: the architecture of the software platform to create digital twins, a set of technologies and tools to implement the platform, methods to automatically construct a digital twin based on the Model-Driven Engineering concept, an algorithm to design an IES based on its digital twin, and principles to organize a computational process using a multi-agent approach. The results of the computational experiment using the software implementation of the IES digital twin components are presented for a test energy supply scheme.

Keywords: digital twin; integrated energy system; ontology; metaprogramming; multi-agent system

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1. Introduction

The establishment of a new energy production structure on the basis of several separately functioning energy (electricity, heat/cooling, gas, and others) systems in the form of an integrated energy system (IES) significantly expands their functionality, ensures the interchangeability of energy carriers, and implements a synergistic effect providing reliable, safe, economical, and environmentally friendly energy supply [1–3]. IES is a sophisticated engineering system characterized by the complex configuration of these systems, a wide range of equipment employed, and the need to provide various operating conditions and coordinate individual systems as subsystems of a single IES. The IESs are systems with a high cost of design, construction, expansion, management, and maintenance during operation. Moreover, these systems are of great importance for the economy and social life of society. Changes in the IESs and control actions on them must be justified and not have negative implications. The listed features of IESs dictate the need to rely on scientifically and theoretically substantiated tools to design and develop them. It is also necessary to apply mathematical tools, which integrate mathematical models, modern methods of computational mathematics, and effective software implementations of algorithms. The study of IES on computer models addresses various IES construction options, which involve building or changing the configuration of a real-world energy system, as well as altering the operating conditions. This allows for avoiding the risks of economic losses and the IES operation conditions that do not meet technical requirements.

Research is underway to build digital twins to design IESs. The digital twins enable modeling in virtual space and considering various IES configurations. The advantage of digital twins is that the properties of a real-world system can be transferred to an object that exists in a virtual space and study this object using computer and mathematical models.

Solving this problem provides an optimal scientifically and economically justified version of the IES, which can be implemented in the construction or development of a real IES (see Figure 1). The use of digital twins allows for enhancing the efficiency of design and boosting the quality of design decisions.

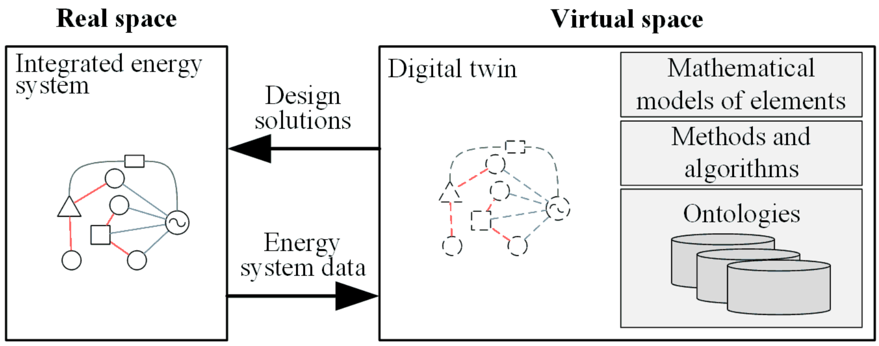

Figure 1. Designing an integrated energy system based on its digital twin.

2. Prerequisites for the Transition to Digital Twins

Objective trends in the structure and properties of future energy systems complicate their manageability. It is also essential to consider the following trends when designing and developing IESs: the power supply quality and reliability requirements increase; the consumer becomes more active (can choose the type of power supply and the type of energy carrier, participate in demand response, and others); the systems switch to real-time remote monitoring of production assets, which is integrated into corporate control systems, to more efficiently optimize operating conditions and improve the processes of operation, repair, and replacement of equipment according to its condition, thereby reducing overall system costs; and the need arises to provide fast processing of a large amount of data to manage the integrated power systems.

The digitalization of infrastructural energy systems develops at a fast pace. There are numerous examples of successful implementation of intelligent digital technologies in power, heat, and gas systems. The advantages of energy digitalization are determined by a significant increase in the reliability of energy supply and the quality of energy and energy services, a radical change in the paradigm of relations between energy supply stakeholders based on the principles of the Internet of Energy, the implementation of large-scale economic effects for all stakeholders, and an increase in the efficiency of decisions made and the performance of company personnel. Efficient intelligent energy systems are impossible without the active involvement of modern advanced information and communication technologies and digital intelligence tools, which provide the possibility of the flexible management of the IES expansion and operation, coordination of subsystems, and accomplishment of system-wide objectives. All this makes energy systems complex cyber-physical systems and points to the need to use digital twins, which operate in the virtual space and have bidirectional connections with the physical space to reflect solutions from one space to the other.

The idea of the digital twin was first proposed by David Gelernter [4], and the digital twin concept was applied to a manufacturing process by Michael Greaves. At present, the term “Digital Twin” means a representation of all components of an object over its life cycle relying on physical data, virtual data, and data on the interaction between them [4–6]. According to experts, the digital twin is one of the promising approaches to the implementation of the Fourth Industrial Revolution (Industry 4.0) [6–10]. Industry 4.0 paradigm suggests the creation of cyber-physical systems and employs the concept of a digital twin and the technology of the Internet of Things, which enhances the efficiency of the maintenance and operation of engineering systems, including energy systems. With digital twins, one can study the behavior of newly installed equipment even before it is installed at real-world energy facilities, its compatibility with other systems, and its impact on them; simulate the most complex technical situations, including equipment failures, changes in energy generation from renewable energy sources and consumer behavior, external influences, and incorrect actions of personnel ([11,12]; etc.). The study presented in Ref. [13] explores the potential of methods and approaches based on digital twins, which are intended to create an intelligent system for optimizing and automating the management of energy consumption in a residential area with the aid of a data model integrated with the Internet of Things, artificial intelligence, and machine learning. Pileggi et al. [8] use the concept of a "cyber-physical power system", in which the power system control relies on digital twins. The findings of the research indicate that the digital twin technology allows for optimizing the size of control actions on the power system and evaluating its operating parameters. The study in Ref. [14] analyzes the impact of maintenance policy optimization on energy efficiency and emissions of harmful substances for both traditional and cyber-physical production systems, with the modeling based on digital twins. Fathy et al. [15] propose a data-driven, multi-layer digital twin of the power grid that aims to reflect the actual energy consumption of households using IoT technologies. The research in [16] develops an approach to the day-ahead prediction of energy consumption by using data obtained from the building's digital twin model. The study in Ref. [17] proposes a DT-based day-ahead scheduling method considering coordination between different power converters in the IES, thereby improving energy efficiency, cost savings, and carbon reduction.

Currently, researchers are actively working on the methodological framework for the creation and use of digital twins. Voropai et al. [18] propose an approach to building an IT infrastructure to create intelligent control systems for the development and operation of energy systems based on the findings of the systems studies in the energy industry, which use modern concepts (digital twins and digital images). Tao et al. [19] make a review of the state of digital twin research in terms of the key components, current developments, and major applications of digital twins in the industry. The study in Ref. [20] identifies the most important requirements for digital twins of industrial energy systems. Currently, there are works examining the specific features of the application of digital twin technology to IES. Li et al. [21] discuss the technical framework for the digital twin technology of integrated energy systems and analyzes its application. Chen et al. [22] explore an approach to using digital twin technologies in an integrated energy system and proposes a hardware-based digital twin solution infrastructure. A digital twin structure is proposed in Ref. [23] to solve IES control problems. The authors present a process of the model generation automation to ensure that the digital model in the virtual space reflects the physical system.

Some researchers suggest using semantic networks to create digital twins [7,24,25]. Ontologies can serve as a basis for developing digital twins. Let us consider examples of ontologies used for the implementation of digital twins. The study in Ref. [26] analyzes the problems of digital twin data management. The authors propose using ontologies to solve these problems. The proposed approach provides the flexibility of knowledge storage throughout the life cycle of the digital twin. The work discussed in [27] presents the general architecture of digital twins of industrial energy systems to ensure flexibility and optimize the operation of these systems. Ontologies are employed to store information about resources and services. A hierarchical approach to design, which consists of an upper-level ontology and a domain ontology, is used. In Ref. [28], ontology is viewed as a representation of a digital twin in the context of cyber-physical systems. In Ref. [29], the prerequisites for applying the ontological approach to building digital twins are considered relying on the results available in the field of ontological engineering of energy systems.

Next, we will consider approaches and software tools for the creation of digital twins. Microsoft has founded the Azure Digital Twins service, which provides the construction of digital twins of real-world objects and uses ontologies to describe them [30]. IBM has developed and implemented a system for creating digital twins "IBM Engineering Lifecycle Optimization" [31] aimed at assessing the technical condition of the equipment. A comprehensive solution enabling the development of digital twins from Siemens is

MindSphere [32]. This solution has functionality for working with energy systems and a wide range of open MindSphere APIs, including analytical services and MindSphere Store with ready-made applications. General Electric develops and implements digital twin technology based on the PREDIX platform [33]. This product is intended for the industry and makes it possible to work with digital twins. The American company Paladin Gateway has developed and implemented the Power Analytics platform [34], which is a set of electrical energy services with the possibility of hosting them in the cloud. These services allow for creating digital twins, exchanging the information obtained by monitoring power systems with management tools. To create a versatile cross-industry environment, ABB has created the ABBAbility product [35] with the aid of the AspectObject technology, through which a digital twin of real-world equipment can be created.

The above review focuses on the studies that reflect the conceptual principles of digital twins, tools, and approaches used in their development and practical application. The advanced experience of creating digital twins in the energy sector has been studied. The review indicates that digital twins of energy facilities are built using ontologies, which bring knowledge into a form suitable for its active use as an independent resource. An analysis of the research on the applicability of the digital twin concept confirms the relevance of digital twins when built for designing integrated energy systems.

3. Principles of Building Digital Twins for Designing Integrated Energy Systems

The digital twin of an IES is an imitation of a real-world physical IES. Therefore, when solving the problems of designing an IES or developing (optimizing) an existing one, its digital twin should reflect the current state of the system, and its possible states in the future in different time periods, for which the scope and sequence of implementation of design solutions are determined in order to achieve the required indices of IESs. The resulting design solutions are based on calculations conducted to find a rational change in the IES, its structure, and parameters, given the set conditions, constraints, and scenarios in question. Digital twins of the IES should make it possible to monitor the dynamics of the IES development over time, build the design solutions for various time periods, and consider possible development scenarios of the system.

When designing an IES with the aid of a digital twin, one should take into consideration that the IESs are complex technical systems and their studies rely on approaches based on hierarchical modeling, which allows for investigating various IESs. IESs consist of various types of energy systems, which are subsystems in the IES. Each of the subsystems contains its set of components. These components can be grouped according to the following energy functions: generation, transmission, distribution, and consumption. In turn, each component has its set of equipment according to the energy functions performed and the type of energy system it belongs to. Modeling is carried out for all subsystems, their set of components, and equipment. At the same time, there are characteristic features of modeling when systems of various types are considered jointly within the IES framework. These features are associated with technical and technological integration solutions, which is why it is necessary to perform modeling of individual subsystems to ensure the coordination of subsystems and the implementation of system-wide targets. The use of hierarchical modeling also provides the possibility for the joint study of systems of different scales, through the aggregation of information on individual systems of a smaller scale and presenting it for the coordination of larger systems, or vice versa, to coordinate the operation of large systems with smaller ones through the disaggregation of information.

In the 1960s, the Soviet scientist Viktor Khasilev [36,37] laid the groundwork for the hydraulic circuit theory, which is a scientific discipline that integrates the achievements of various branches of science to build a common physical and mathematical basis for the analysis, design, and control of pipeline systems. Within the framework of the study presented in the paper, this theory underlies the modeling of pipeline systems of various types and purposes as part of the IES. The IES modeling requires flexible organization of the computational process in order to take into account the dynamics of changes in the energy supply parameters for the IES subsystems during the calculation period, the presence of active components and subsystems in the IES, and to coordinate their work. In [38], an approach based on multi-agent technologies is proposed to model the IES considering the described features.

A unified methodological approach needs to be developed to combine mathematical models and methods of the hydraulic circuit theory and electric circuit theory [39], i.e., an approach to IES modeling based on multi-agent technologies into a single methodological framework. The software implementation of this approach poses a problem associated with the high difficulty of keeping up to date the entire set of necessary software components, which implement mathematical models of the equipment of various IES subsystems. To overcome this problem, it is necessary to involve programming paradigms focused on the automation of the software design stages. Based on the research, the Model-Driven Engineering (MDE) methodology is proposed, which represents a set of principles and approaches to the automated construction of complex software systems based on pre-developed models [40–42].

Energy systems of a certain type have these type-specific properties, a set of applied problems, and dedicated software used to solve them. Knowledge about them must be stored in a form suitable for processing by software systems and used in solving various design problems. To do this, it is necessary to organize the storage of this knowledge in the form of ontologies [40,43,44]. The construction and application of digital twins rely on ontologies that enable a formal description of the domain objects, their properties, and the relationship between these objects.

The construction principles of digital twins intended to solve the IES design problems include:

- Complex engineering calculations are done to find the best ways to transform the IESs in order to improve the efficiency and reliability of their operation;
- Modeling of IES, including various types of energy systems with their individual characteristics, given the hierarchical principle of its construction;
- A single information space organized to solve the IES design problems;
- Bidirectional communication between the external environment and the digital twin of the IES to track changes and update information in the digital twin and generate IES design solutions;
- Tracking the dynamics of IES development over time;
- Consideration of the plurality of decision-making centers for the supply of energy of various types with the possibility of converting one type into another one when solving the IES design problems;
- The need to consider a large number of IES components with complex behavior;
- The knowledge about the IES, its subsystems, the software used, and the features of solving the IES design problems.

4. Approach to Designing an Integrated Energy System Based on Its Digital Twin

A methodological approach to designing an integrated energy system based on its digital twin is developed based on the principles formulated in Section 3. The proposed approach involves the construction of a computer model of the IES by an engineer. Based on this model, a digital twin is built in an automated mode, and the simulation results obtained with the digital twin are used to prepare real design solutions and, ultimately, build a real-world IES. In turn, with the data on the characteristics of a real-world IES, its computer model can be built and used to create a digital twin in an automated mode.

This methodological approach includes the following components:

- An architecture of the software platform for creating digital twins;
- A set of technologies and tools for the platform implementation;
- Methods for automated construction of a digital twin based on the MDE concept;
- An algorithm for solving the problem of IES design based on its digital twin;
- Principles of organization of the computational process using the multi-agent approach.

The architecture of the software platform for creating digital twins is shown in Figure 2.

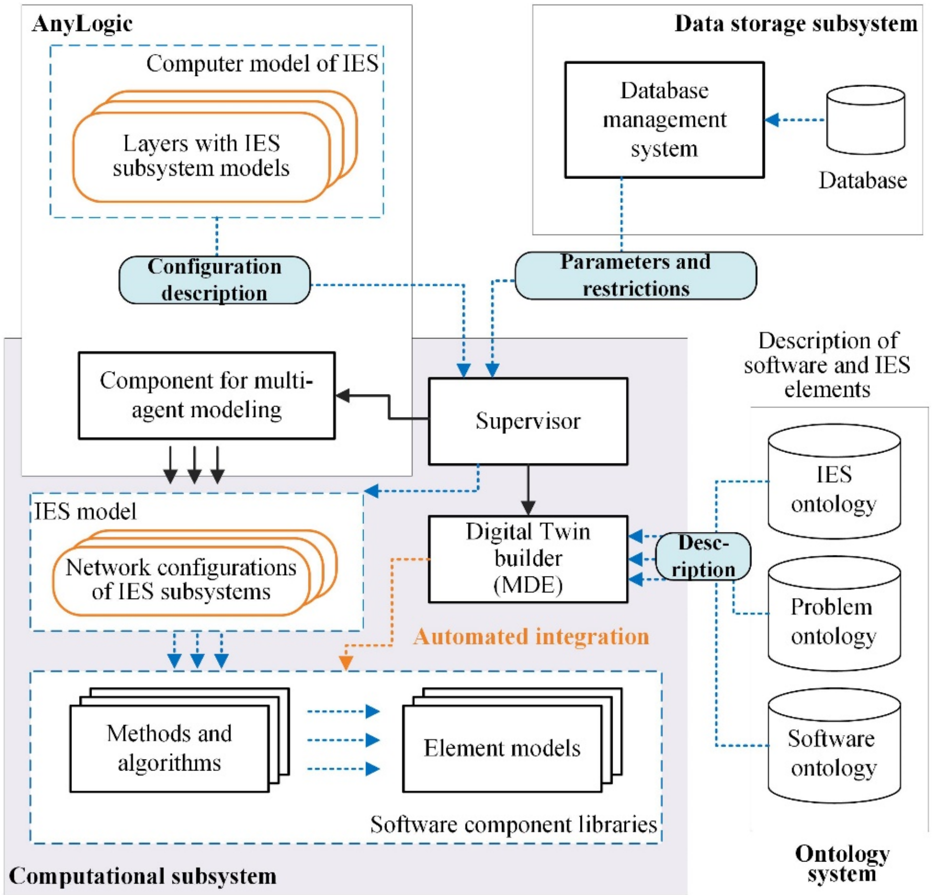

Figure 2. The architecture of the software platform for creating IES digital twins.

The development of a methodological approach to building a software platform relies on elements of structural, object-oriented, and component-oriented programming, the theory of algorithms, and database theory. The Java programming language, the JDK compiler, mathematical libraries (Parallel Colt, JAMA, Lpsolve, etc.), the Eclipse development environment, and the Firebird database management system are used as software implementation tools. Java is used as the base programming language because it has the following advantages: (1) it supports modern technologies of object-oriented, component, and functional programming; (2) it has built-in support for metaprogramming technologies; and (3) it has a wide range of technologies and tools to provide distributed and parallel computing. The software platform is developed relying solely on free software.

The methods proposed to build the software platform are based on the Model-Driven Engineering (MDE) concept of software development. This concept is further developed through the adaptation to the IES design objectives and the use of ontologies and modern metaprogramming technologies that provide high flexibility to dynamically design the components of a software system and make necessary changes to it [45,46].

The main steps of the proposed algorithm for designing an IES based on its digital twin are shown in Figure 3.

Step I suggests building a computer model of an IES based on the given initial data. The computer IES model can be represented as an aggregate of a graph, which describes the configuration of this system, and a set of graphical and mathematical models, which define the properties of its subsystems and components.

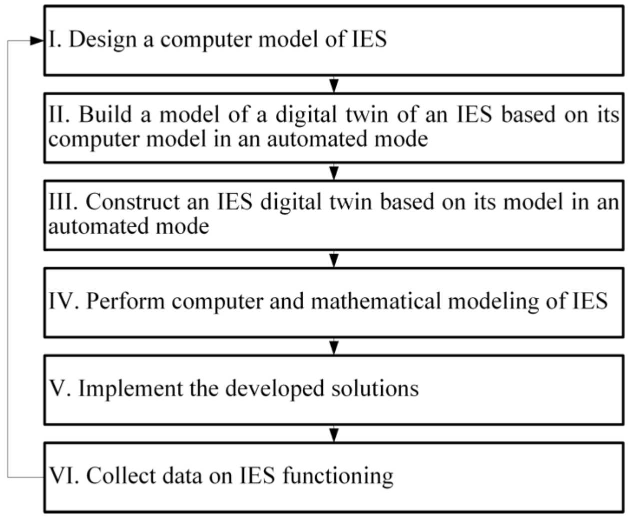

Figure 3. Diagram of the algorithm for solving the problem of IES design based on its digital twin.

Step II involves creating a model of the IES digital twin in an automated mode based on the knowledge stored in the form of a system of ontologies. This model includes the following components:

- Description of data structures of IES and its subsystems;
- Description of software components that implement mathematical models and methods for solving an applied problem;
- A graph describing the computational process;
- A set of data structures, which describes input and output parameters.

Step III is responsible for the automated construction of a digital twin based on its model using the knowledge stored in the form of a system of ontologies.

Digital twin is a way of organizing a space for solving a set of applied problems, including the following components:

- Computer model of the IES (data structures describing the configuration of the system and the properties of its constituent components);
- Mathematical tools (including mathematical models and algorithms);
- Software components (graphic, system, applied mathematical, typical models of components of the IES subsystems) integrated into a single software system;
- Interactive graphical user interface, including a graphical computer model;
- Data storage that contains the values of the properties of the system and its components at different points in time;
- System of data exchange with the external environment.

The construction of a digital twin is an automated integration of its listed components into a single information space. The concept of MDE is the basis for the automated construction of a digital twin. A specific feature of this concept implementation within the framework of the developed approach is the wide use of modern metaprogramming technologies [47,48], which provide high flexibility for the dynamic design of the software system components and necessary changes in the system.

Step IV involves computer and mathematical modeling of the IES using a multi-agent approach [38,49,50], mathematical models, and algorithms, which are implemented as software components. The computational process is controlled by knowledge from the ontology system and runs in an automated mode. The modeling will provide the data based on which the design solutions will be prepared for newly designed IES or existing IES to be optimized.

Step V implements the obtained design solutions in practice to build an IES.

Step VI provides the collection of data on the characteristics of IESs during their operation in various periods of time. Next, the transition to Step I is made to refine the computer model of the IES using the collected data.

The principles of a computational process based on the multi-agent approach are proposed. This computational process allows for modeling the changes in the dynamics of the IES development and functioning over time, considering a great number of decision-making centers for the supply of various types of energy with the possibility of conversion from one type to another. According to the proposed principles, objects in the IES are divided into three groups: consumers, networks, and energy sources. Each object is represented by its agent, which reflects its behavior in the system, links with other agents, characteristics, parameters, and individual restrictions. The hierarchy of interaction between agents is described by three levels (see Figure 4). At the first level (the level of development), there is a development agent and its auxiliary local agents (an agent for the development of energy sources, a network development agent, and a diagram construction agent).

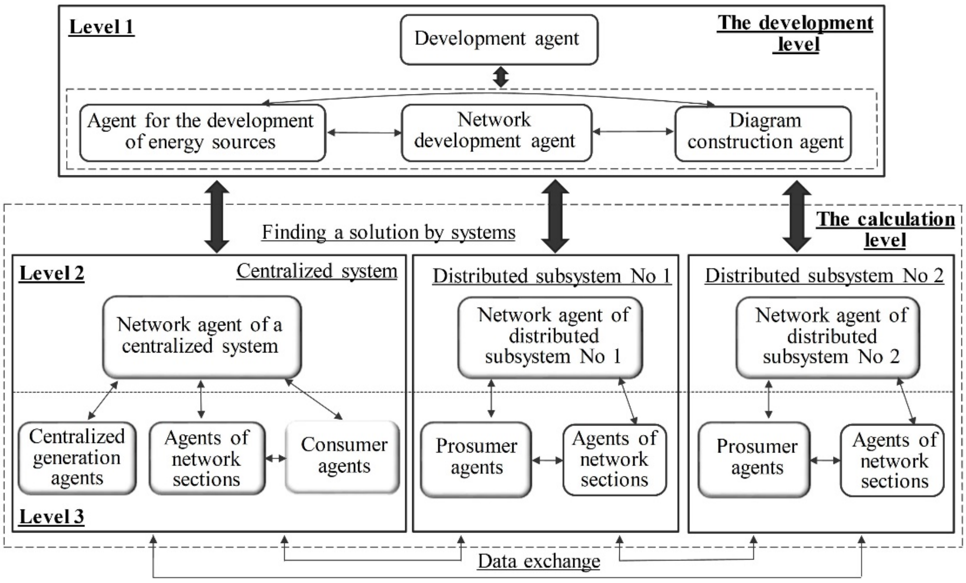

Figure 4. The structure of a multi-agent system for solving the development problem.

The agents of the development level prepare data for the calculated scheme, generate a redundant IES scheme, and send the necessary data to the calculation level, then analyze the received data and generate a solution for the IES development. They also display statistics in the form of graphs and diagrams to users. The second and third levels of functioning of the objects are combined at the calculation level. At the second level, there are coordinating agents: a network agent of a centralized system and network agents of distributed subsystems. The network agent of the centralized system coordinates and controls the formation of a solution for centralized generation facilities. It exchanges information with the development agent and network agents of distributed subsystems. Distributed generation sources located at prosumers are coordinated and controlled by network agents of distributed subsystems. They, in turn, exchange data on the generated solution with the development agent and the network agent of the centralized system. If necessary, the network agent of the centralized system and the network agents of the distributed subsystems correct the obtained solutions. At the third level, there are consumer agents, agents of network sections, centralized generation agents, and prosumer agents. They simulate the operation of IES objects and participate in the formation of a solution for their subsystems, by exchanging data with the agents associated with them.

5. Implementation of the Digital Twin of the Integrated Energy System

The software implementation of individual components of the IES digital twin is performed. A multi-agent IES model is built in the AnyLogic software environment. The developed multi-agent model is applied to run a computational experiment on the development of IES. The scheme of the modelled IES is shown in Figure 5. It includes the following components: ordinary consumers and prosumers, electric boilers, photovoltaic systems, power transmission lines, heat mains, gas mains, electrical and heating energy sources, and a gas distribution station.

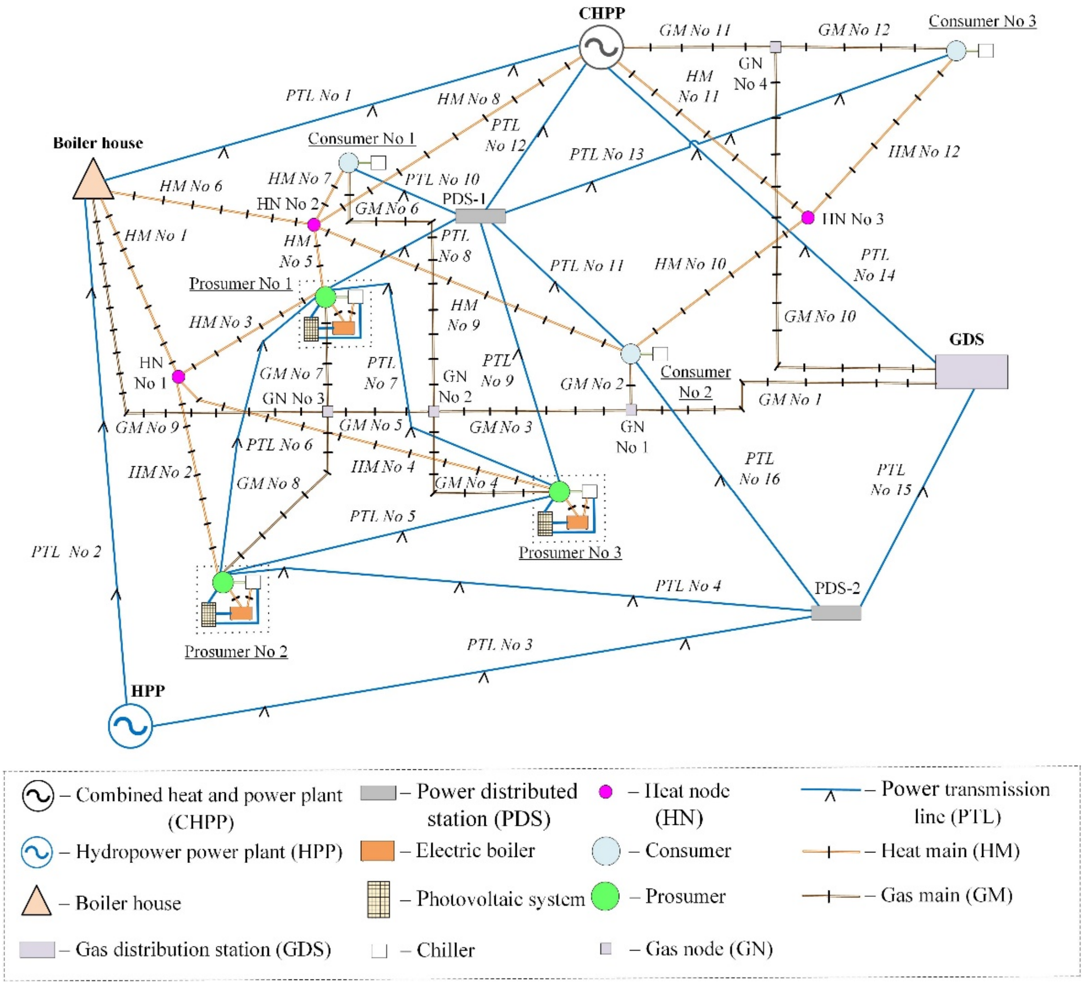

Figure 5. The scheme of the modelled integrated energy system.

The problem of the modelled IES development is solved by using the software components developed by us. These software components are dynamically integrated within a single computing process based on knowledge from ontologies. The interaction between agents and software components used in the multi-agent system provided an optimal solution, based on which the necessary measures for the construction of the network and generating facilities were determined and implemented. A visual representation of the obtained solution is shown in Figure 6, the network sections involved in the energy supply are highlighted in the corresponding color. The calculation results are presented in Tables 1–3. The computational experiment indicates the possibility of using a digital twin to solve the problem of IES development.

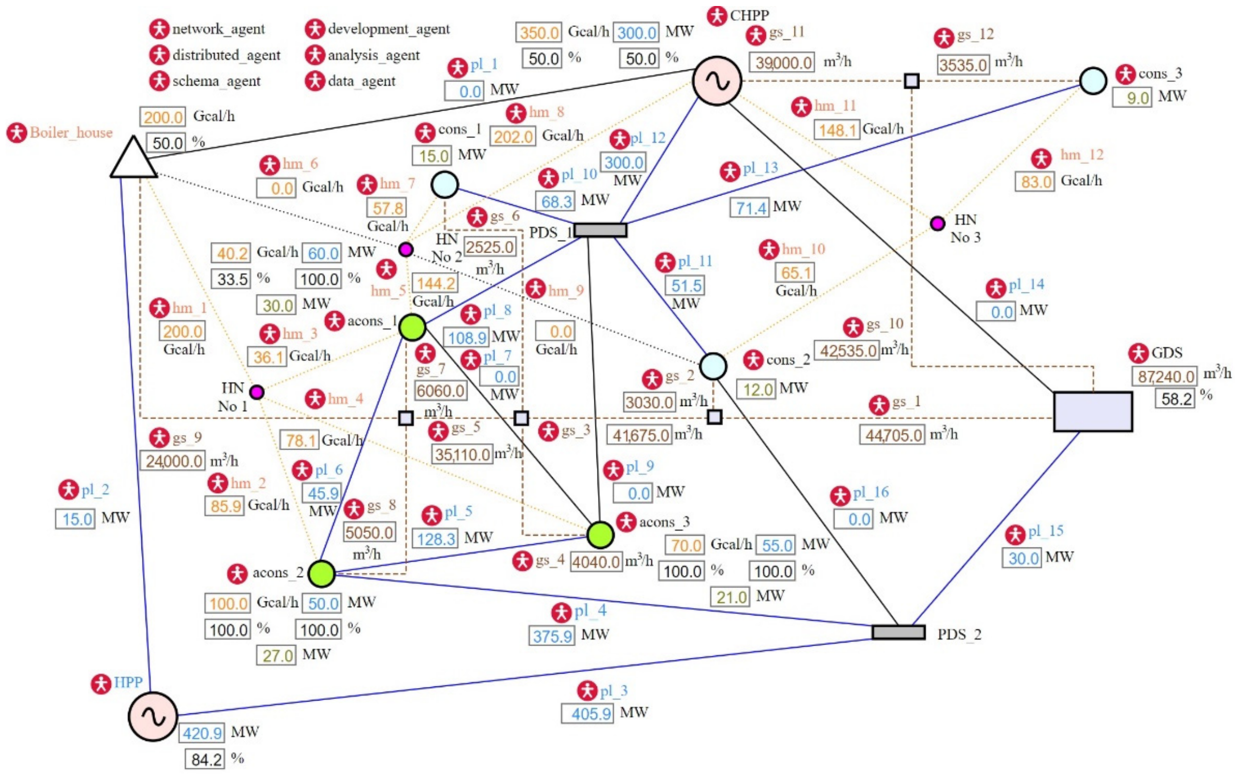

Figure 6. Results of the integrated energy system calculation.

Table 1. Calculation results for energy sources.

Name	Heat Generation, Gcal/h	Electricity Generation, MW	Gas Supply, m^3/h	Workload, %
CHPP	350.0	300.0	-	50.0
HPP	-	420.9	-	84.2
Boiler house	200.0	-	-	50.0
GDS	-	-	87,240.0	58.2

Table 2. Calculation results for prosumers.

Name	Electrical Load, MW	Heat Load, Gcal/h	Gas Load, m^3	Cold Load, MW	Heat Generation, Gcal/h	Electricity Generation, MW	Cold Generation, MW
Prosumer No 1	150.0	180.0	6000.0	30.0	40.2	60.0	30.0
Prosumer No 2	120.0	150.0	5000.0	27.0	100.0	50.0	27.0
Prosumer No 3	90.0	120.0	4000.0	21.0	70.0	55.0	21.0

The costs for energy supply of prosumers with the found configuration of the IES are shown in Figure 7. The values are given for three prosumers for electricity supply, heat supply, and gas supply (cooling costs are included in the costs of electricity and heat supply). The total energy supply costs for the first prosumer amounted to EUR 9313.99, for the second prosumer they were EUR 7400.98, and for the third prosumer, they were equal to EUR 5793.82. The total energy supply cost for the three prosumers was EUR 22,508.8.

Table 3. Calculation results for network sections.

Name TPL	Electric Power Flow, MW	Name HM	Heat Transfer, Gcal/h	Name GM	Gas Flow Rate, m^3/h
TPL No 1	0.0	HM No 1	200.0	GM No 1	44,705.0
TPL No 2	15.0	HM No 2	85.9	GM No 2	3030.0
TPL No 3	405.9	HM No 3	36.1	GM No 3	41,675.0
TPL No 4	375.9	HM No 4	78.1	GM No 4	4040.0
TPL No 5	128.3	HM No 5	144.2	GM No 5	35,110.0
TPL No 6	45.9	HM No 6	0.0	GM No 6	2525.0
TPL No 7	0.0	HM No 7	57.8	GM No 7	6060.0
TPL No 8	108.9	HM No 8	202.0	GM No 8	5050.0
TPL No 9	0.0	HM No 9	0.0	GM No 9	24,000.0
TPL No 10	68.3	HM No 10	65.1	GM No 10	42,535.0
TPL No 11	51.5	HM No 11	148.1	GM No 11	39,000.0
TPL No 12	300.0	HM No 12	83.0	GM No 12	3535.0
TPL No 13	71.4	-	-	-	-
TPL No 14	0.0	-	-	-	-
TPL No 15	30.0	-	-	-	-
TPL No 16	0.0	-	-	-	-

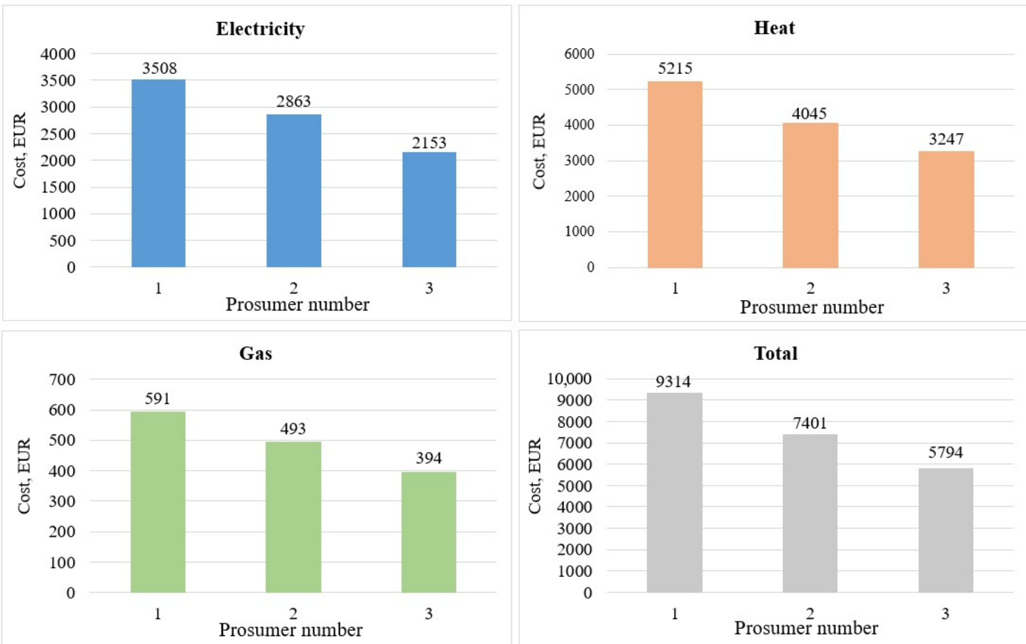

Figure 7. The energy costs for prosumers.

6. Conclusions

Integrated energy systems grow in significance due to their high importance for industry and utilities. In today's context, the optimal design of these systems, which has a scientific, engineering, and economic justification, becomes ever-relevant. The design of IES is a challenge due to the highly complex configuration of these systems, a wide range of equipment employed, and a diverse set of mathematical models and dedicated software used to model it. The use of digital twins enables an effective exploration of various objects, providing the formation of their various options in the virtual space, thereby allowing more effective design solutions to be created.

This paper proposes the principles of building digital twins to design IES. These principles are used in the study to develop a methodological approach to designing an

IES based on its digital twin. Within the framework of this approach, the architecture of the software platform for creating digital twins has been developed. A set of modern technologies and tools for the implementation of the software platform is proposed. Methods for the automated construction of a digital twin based on the MDE concept have been developed, following the design features of the IES. MDE implementation relies on formalized knowledge in the form of ontologies and modern metaprogramming technologies. An algorithm for solving the problem of IES design based on its digital twin has been developed. The principles are proposed to organize a computing process using a multi-agent approach, which allows for selecting of the configuration and equipment parameters for the IES, considering the dynamics of changes in the characteristics of its subsystems and components.

The results obtained during the computational experiment using the software implementation of the IES digital twin components are presented for a test energy supply scheme. The experiment performed with the developed digital twin has allowed for building an optimal IES diagram for energy supply to consumers, considering the system conditions and constraints.

This methodological approach can be applied by research, design, and operation organizations engaged in the reconstruction and expansion of IESs. Its application can enhance the efficiency of the design process, improve the quality of the resulting design solution, and automate labor-intensive computational operations performed when selecting the parameters and configuration of an IES under design.

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References

1. Stennikov, V.; Barakhtenko, E.; Sokolov, D.; Zhou, B. Current state of research on the energy management and expansion planning of integrated energy systems. *Energy Rep.* **2022**, *8*, 10025–10036. [CrossRef]
2. Voropai, N.I.; Stennikov, V.A.; Barakhtenko, E.A. Integrated energy systems: Challenges, trends, philosophy. *Stud. Russ. Econ. Dev.* **2017**, *28*, 492–499. [CrossRef]
3. Voropai, N.I.; Stennikov, V.A.; Barakhtenko, E.A. Methodological principles of constructing the integrated energy supply systems and their technological architecture. *J. Phys. Conf. Ser.* **2018**, *1111*, 012001. [CrossRef]
4. Gelernter, D. *Mirror Worlds: Or the Day Software Puts the Universe in a Shoebox. How It Will Happen and What It Will Mean*; Oxford University Press: Oxford, UK, 1993.
5. Tao, F.; Sui, F.; Liu, A.; Qi, Q.; Zhang, M.; Song, B.; Guo, Z.; Lu, S.C.-Y.; Nee, A.Y.C. Digital twin-driven product design framework. *Int. J. Prod. Res.* **2019**, *57*, 3935–3953. [CrossRef]
6. Lim, K.Y.H.; Zheng, P.; Chen, C. A state-of-the-art survey of Digital Twin: Techniques, engineering product lifecycle management and business innovation perspectives. *J. Intell. Manuf.* **2020**, *31*, 1313–1337. [CrossRef]
7. Sharif Ullah, A.M.M. Modeling and simulation of complex manufacturing phenomena using sensor signals from the perspective of Industry 4.0. *Adv. Eng. Inform.* **2019**, *39*, 1–13. [CrossRef]
8. Pileggi, P.; Verriet, J.; Broekhuijsen, J.; van Leeuwen, C.; Wijbrandi, W.; Konsman, M. A Digital Twin for Cyber-Physical Energy Systems. In Proceedings of the 7th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, Montreal, QC, Canada, 5–15 April 2019; IEEE: New York, NY, USA, 2019. [CrossRef]
9. Xu, X. Machine Tool 4.0 for the New Era of Manufacturing. *Int. J. Adv. Manuf. Technol.* **2017**, *92*, 1893–1900. [CrossRef]

10. Zambrano, V.; Mueller-Roemer, J.; Sandberg, M.; Talasila, P.; Zanin, D.; Larsen, P.G.; Loeschner, E.; Thronicke, W.; Pietraroia, D.; Landolfi, G.; et al. Industrial digitalization in the industry 4.0 era: Classification, reuse and authoring of digital models on Digital Twin platforms. *Array* **2022**, *14*, 100176. [CrossRef]
11. Karanjkar, N.; Joglekar, A.; Mohanty, S.; Prabhu, V.; Raghunath, D.; Sundaresan, R. Digital Twin for Energy Optimization in an SMT-PCB Assembly Line. In Proceedings of the 2018 IEEE International Conference on Internet of Things and Intelligence System, Bali, Indonesia, 1–3 November 2018; IEEE: New York, NY, USA, 2018. [CrossRef]
12. Katsidoniotaki, E.; Psarommatis, F.; Göteman, M. Digital Twin for the Prediction of Extreme Loads on a Wave Energy Conversion System. *Energies* **2022**, *15*, 5464. [CrossRef]
13. Agostinelli, S.; Cumo, F.; Guidi, G.; Tomazzoli, C. Cyber-Physical Systems Improving Building Energy Management: Digital Twin and Artificial Intelligence. *Energies* **2021**, *14*, 2338. [CrossRef]
14. Bányai, Á.; Bányai, T. Real-Time Maintenance Policy Optimization in Manufacturing Systems: An Energy Efficiency and Emission-Based Approach. *Sustainability* **2022**, *14*, 10725. [CrossRef]
15. Fathy, Y.; Jaber, M.; Nadeem, Z. Digital Twin-Driven Decision Making and Planning for Energy Consumption. *J. Sens. Actuator Netw.* **2021**, *10*, 37. [CrossRef]
16. Henzel, J.; Wróbel, Ł.; Fice, M.; Sikora, M. Energy Consumption Forecasting for the Digital-Twin Model of the Building. *Energies* **2022**, *15*, 4318. [CrossRef]
17. You, M.; Wang, Q.; Sun, H.; Castro, I.; Jiang, J. Digital twins based day-ahead integrated energy system scheduling under load and renewable energy uncertainties. *Appl. Energy* **2022**, *305*, 117899. [CrossRef]
18. Voropai, N.I.; Massel, L.V.; Kolosok, I.N.; Massel, A.G. IT-Infrastructure for Construction of Intelligent Management Systems of Development and Functioning of Energy Systems Based on Digital Twins and Digital Images. *Izv. Ross. Akad. Nauk. Energ.* **2021**, *1*, 3–13. (In Russian) [CrossRef]
19. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform.* **2019**, *15*, 2405–2415. [CrossRef]
20. Kasper, L.; Birkelbach, F.; Schwarzmayr, P.; Steindl, G.; Ramsauer, D.; Hofmann, R. Toward a Practical Digital Twin Platform Tailored to the Requirements of Industrial Energy Systems. *Appl. Sci.* **2022**, *12*, 6981. [CrossRef]
21. Li, H.; Zhang, T.; Huang, Y. Digital Twin Technology for Integrated Energy System and Its Application. In Proceedings of the 1st International Conference on Digital Twins and Parallel Intelligence), Beijing, China, 15 July–15 August 2021; IEEE: New York, NY, USA, 2021. [CrossRef]
22. Chen, Y.; Chen, Q.; Gao, J.; Li, Z.; Chen, X. Hardware-in-loop based Digital Twin Technology for Integrated Energy System: A Case Study of Guangyang Island in Chongqing. In Proceedings of the 5th International Electrical and Energy Conference, Nangjing, China, 27–29 May 2022; IEEE: New York, NY, USA, 2022. [CrossRef]
23. Bai, H.; Yuan, Z.; Tang, X.; Liu, J.; Yang, W.; Pan, S.; Xue, Y.; Liu, W. Automatic Modeling and Optimization for The Digital twin of a Regional Multi-energy System. In Proceedings of the Power System and Green Energy Conference, Shanghai, China, 25–27 August 2022; IEEE: New York, NY, USA, 2022. [CrossRef]
24. Kannan, K.; Arunachalam, N. A Digital Twin for Grinding Wheel: An Information Sharing Platform for Sustainable Grinding Process. *J. Manuf. Sci. Eng.* **2019**, *141*, 021015. [CrossRef]
25. Moreno, A.; Velez, G.; Ardanza, A.; Barandiaran, I.; de Infante, Á.R.; Chopitea, R. Virtualisation process of a sheet metal punching machine within the Industry 4.0 vision. *Int. J. Interact. Des. Manuf.* **2017**, *11*, 365–373. [CrossRef]
26. Singh, S.; Shehab, E.; Higgins, N.; Fowler, K.; Reynolds, D.; Erkoyuncu, J.A.; Gadd, P. Data management for developing digital twin ontology model. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2020**, *235*, 2323–2337. [CrossRef]
27. Steindl, G.; Stagl, M.; Kasper, L.; Kastner, W.; Hofmann, R. Generic Digital Twin Architecture for Industrial Energy Systems. *Appl. Sci.* **2020**, *10*, 8903. [CrossRef]
28. Steinmetz, C.; Rettberg, A.; Ribeiro, F.G.C.; Schroeder, G.; Pereira, C.E. Internet of Things Ontology for Digital Twin in Cyber Physical Systems. In Proceedings of the VIII Brazilian Symposium on Computing Systems Engineering, Salvador, Brazil, 5–8 November 2018; IEEE: New York, NY, USA, 2018. [CrossRef]
29. Massel, L.; Vorozhtsova, T. An ontological approach to the construction of digital twins of energy objects and systems. *Ontol. Proekt.* **2020**, *10*, 327–337. (In Russian) [CrossRef]
30. Azure Digital Twins. Available online: https://docs.microsoft.com/en-us/azure/digital-twins/ (accessed on 1 September 2022).
31. IBM Engineering Lifecycle Optimization. Available online: https://www.ibm.com/ru-ru/products/engineering-lifecycle-optimization/engineering-insights (accessed on 1 September 2022).
32. Siemens, MindSphere. Available online: https://new.siemens.com/ru/ru/produkty/programmnoe-obespechenie/mindsphere.html (accessed on 1 September 2022).
33. GE, PREDIX. Available online: https://www.ge.com/digital/applications/digital-twin (accessed on 1 September 2022).
34. Power Analytics. Available online: https://www.poweranalytics.com/paladin-software/ (accessed on 1 September 2022).
35. ABB, ABBAbility. Available online: https://new.abb.com/abb-ability/ru (accessed on 1 September 2022).
36. Khasilev, V.Y. Elements of the theory of hydraulic circuits. *Bull. USSR Acad. Sci. Energy Transp.* **1964**, 69–88. (In Russian)
37. Merenkov, A.P.; Khasilev, V.Y. *Theory of Hydraulic Circuits*; Nauka: Moscow, Russia, 1985. (In Russian)
38. Stennikov, V.; Barakhtenko, E.; Mayorov, G.; Sokolov, D.; Zhou, B. Coordinated management of centralized and distributed generation in an integrated energy system using a multi-agent approach. *Appl. Energy* **2022**, *309*, 118487. [CrossRef]

39. Yorke, R. *Electric Circuit Theory*; Pergamon Press: Oxford, UK, 1981. [CrossRef]
40. Staab, S.; Walter, T.; Gröner, G.; Parreiras, F.S. Model driven engineering with ontology technologies. Reasoning Web. In *Reasoning Web 2010: Reasoning Web. Semantic Technologies for Software Engineering*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 62–98. [CrossRef]
41. Brambilla, M.; Cabot, J.; Wimmer, M. Model-driven software engineering in practice. In *Synthesis Lectures on Software Engineering*; Morgan & Claypool: Kentfield, CA, USA, 2012.
42. Silva da, A.R. Model-driven engineering: A survey supported by the unified conceptual model. *Comput. Lang. Syst. Struct.* **2015**, *43*, 139–155. [CrossRef]
43. Gruber, T.R. A translation approach to portable ontology specifications. *Knowl. Acquis.* **1993**, *5*, 199–220. [CrossRef]
44. Staab, S.; Studer, R. *Handbook on Ontologies*, 2nd ed.; Springer: Heidelberg, Germany, 2009. [CrossRef]
45. Stennikov, V.A.; Barakhtenko, E.A.; Sokolov, D.V. A Methodological Approach to the Software Development for Heating System Design. In Proceedings of the International Multi-Conference on Industrial Engineering and Modern Technologies, Vladivostok, Russia, 3–4 October 2018; IEEE: New York, NY, USA, 2018. [CrossRef]
46. Stennikov, V.A.; Barakhtenko, E.A.; Sokolov, D.V. Development of Information and Technology Platform for Optimal Design of Heating Systems. In Proceedings of the 7th Scientific Conference on Information Technologies for Intelligent Decision Making Support, Ufa, Russia, 28–29 May 2019; Atlantis Press: Paris, France, 2019. [CrossRef]
47. Hazzard, K.; Bock, J. *Metaprogramming in NET*; Manning Publications: Shelter Island, NY, USA, 2013.
48. Lämmel, R. *Software Languages: Syntax, Semantics, and Metaprogramming*; Springer: Cham, Switzerland, 2018.
49. Ren, Y.; Fan, D.; Feng, Q.; Wang, Z.; Sun, B.; Yang, D. Agent-based restoration approach for reliability with load balancing on smart grids. *Appl. Energy* **2019**, *249*, 46–57. [CrossRef]
50. Zhang, Z.; Jing, R.; Lin, J.; Wang, X.; van Dam, K.H.; Wang, M.; Meng, C.; Xie, S.; Zhao, Y. Combining agent-based residential demand modeling with design optimization for integrated energy systems planning and operation. *Appl. Energy* **2020**, *263*, 114623. [CrossRef]