Energy Systems Research

Volume 5 · Number 3 · 2022

Published by
Melentiev Energy Systems Institute
Siberian Branch of Russian Academy of Sciences

Available online: esrj.ru

ISSN 2618-9992

Energy Systems Research

Volume 5 • Number 3 • 2022
International scientific peer-reviewed journal
Available online: http://esrj.ru

About the journal

Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

Energy systems research methodology is based on a systems approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of systems analysis.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

The journal welcomes papers on advances in heat and electric power industries, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technologies.

Energy Systems Research is also concerned with energy systems challenges related to the applications of information and communication technologies, including intelligent control and cyber security, modern approaches of systems analysis, modeling, forecasting, numerical computations and optimization.

The journal is published by Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences. The journal's ISSN is 2618-9992. There are 4 issues per year (special issues are available). All articles are available online on English as Open access articles.

Topics

- Energy production, conversion, transport and distribution systems
- Integrated energy systems
- Energy technologies
- International, regional, local energy systems
- Energy system protection, control and management
- Smart energy systems, smart grids
- Energy systems reliability and energy security
- Electricity, heating, cooling, gas and oil systems
- Energy system development and operation
- Demand-side management
- Energy economics and policy
- Renewable energy and clean fossil fuel based systems
- Distributed energy systems
- Sustainable energy transitions
- System problems of power and thermal engineering
- Artificial intelligence in energy systems
- Information and communication technologies in energy systems
- Energy systems analysis and modelling
- Computational methods and optimization in energy systems

Publishing board

Executive secretary:	Dmitry Zolotarev
Copyeditor:	Marina Ozerova
Math proofreading editor	Evgenia Markova

Contacts

Scientific secretary:	Alexey Mikheev, Dr. of Eng.
E-mail:	info@esrj.ru
Tel:	+7 (3952) 950980 (English, Russian)
Fax:	+7 (3952) 426796
Address:	130, Lermontov str., Irkutsk, 664033, Russia

Contents

Development of a Web Service for Analysis of the GeoGIPSAR Geoclimatic Data

E.N. Osipchuk [1,*], V.S. Gasan

[1] Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The paper discusses the creation of a Web service for the information prognostic system GeoGIPSAR developed at the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (MESI SB RAS). It relies on the data from modern global climate models (such as NOAA, GPCC, etc.) to predict inflow in the reservoirs of the Angara-Yenisei hydropower plant cascade. The disadvantages of the GeoGIPSAR are its limited interface (mostly understandable only to specialists) and local mode, which does not involve working on the Internet. The Web service at issue is being currently developed to expand a range of the system users. A review of modern systems for working with global climate models is presented. The main GeoGIPSAR functions and data used for the analysis of geoclimatic indicators are considered. The requirements for the basic controls of the developed Web service are considered. The development technologies applied are described. The climate maps created by the system for the Lake Baikal basin are shown as examples.**

***Index Terms*: forecasting, geoclimatic data, monitoring, web service.**

I. Overview of Web Systems for Geoclimatic Data Analysis

Over the past decades, there have been significant advances in climate monitoring and forecasting. However, there are no reliable universal methods for their application in practice, for example, in the energy sector. Global climate change has significantly affected many regional processes that influence the efficiency of energy systems: changes in statistical data of inflows, temperatures, precipitation, etc. The long-term planning of electricity generation at hydropower plants and energy balances usually relies on the runoff rate estimates based on accumulated statistical data. The extreme or prolonged low-water and high-water periods complicate such estimation, which requires new approaches.

MESI SB RAS has developed and is improving an approach to creating reliable predictive estimates of water content in reservoirs and modeling of future HPP regimes based on them [1–3]. The information prognostic system GeoGIPSAR [4, 5] makes it possible to carry out a comprehensive spatial and time analysis of meteorological and hydrological data with creation of prognostic scenarios of water content in the reservoirs of the Angara-Yenisei cascade [6, 7]. The disadvantage of the system is its limited interface (more understandable only to specialists) and local mode, which does not involve working on the Internet.

Modern technologies for global monitoring and forecasting of the state of the climate, together with the emerging open Geographic Information Systems (GIS), provide a new level of natural and climatic data analysis. Examples of well-known and convenient services that ensure access to work with geoclimatic data, including high-quality visualization, are as follows:

Ventusky [8] is an example of a modern system for monitoring and forecasting global meteorological indicators and weather changes over time throughout the globe and at individual locations. It was created by the Czech company InMeteo, which specializes in meteorology and visualization of weather indicators collected from various satellites and weather towers. Initially, the specialists focused on the weather in the Czech Republic alone, but later launched a worldwide project. Ventusky maps allow the user to visualize the interrelation between weather conditions in different parts of the world through dynamic illustrations. The service also contains a separate application that includes a classic weather forecast for a specific location. The uniqueness of the application lies in the large amount of data displayed: precipitation forecast, wind speed, cloudiness, atmospheric pressure, snow cover, and other meteorological data for different heights above sea level.

---

* Corresponding author.
E-mail: eugene.os@mail.ru

http://dx.doi.org/10.38028/esr.2022.03.0001
Received September 10, 2022. Revised September 21, 2022. Accepted September 30, 2022. Available online December 5, 2022.

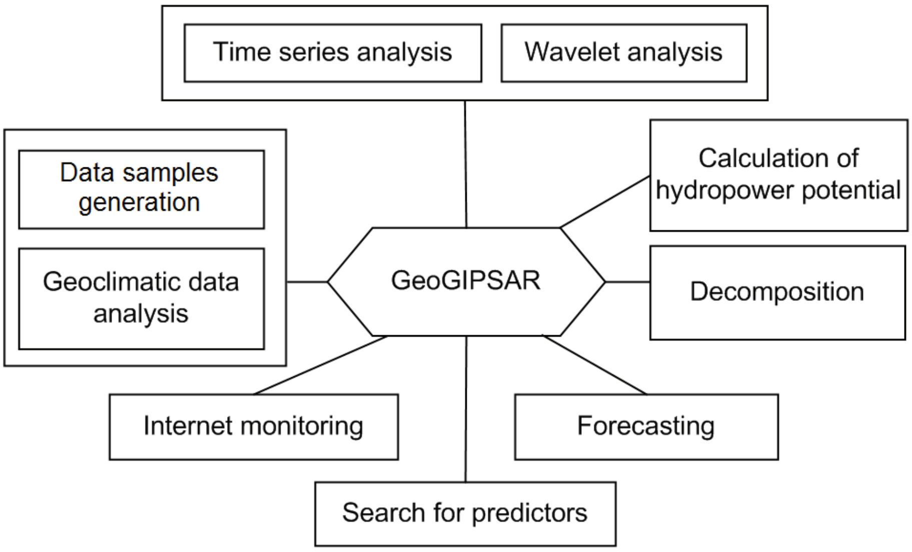


Fig. 1. Main functions of the GeoGIPSAR.

Nullschool [9] is one of the first services created with dynamic 3D visualization maps of global weather conditions, which works directly in the browser. The service includes a universal map that can be rotated and scaled in real time. It shows wind movement, air pollution, wave heights, and more. The data is updated every 3 hours for land and every 5 days for ocean surface parameters.

Windy [10] is a Czech company providing interactive weather forecasting services worldwide. In terms of functions, Windy is close to the Ventusky service, but is more focused on wind animation, for which it was originally created. Currently, there are other basic meteorological parameters such as temperature, pressure, relative humidity, cloud base, and additional sources with extended data.

EarthAtlas [11] is an example of a modular map service developed by the University of New Hampshire (the USA). It is designed to provide the user with access to and interaction with various Earth data and water layer modeling results. EarthAtlas is part of an application that provides its own full-featured Web service, including customization of styles, map types, mapping tools, selection of datasets, layers, and others. The main purpose and functionality of EarthAtlas is the dynamic display of maps that contain raster and vector polygonal datasets (spatial coverage of observational or modeling data), and point datasets (from stations and objects).

Meteologix [12] is a European service that has forecast data from various global models with the display of various indicators, images from space, and forecasts for the whole world. The uniqueness of the service is a large set of predictive models from different countries.

Lobelia.earth [13] is a European service where user can work with Earth observations and climate models for risk analysis and climate scenario assessments using the ERA5 dataset. It provides hourly estimates of a large number of atmospheric, terrestrial, and oceanic climate variables (covering the Earth's atmosphere on a 30 km grid using 137 levels from the surface to an altitude of 80 km).

Despite powerful visualization tools and extensive GIS tools, these systems are difficult to apply to assess indicators in a given area (e.g. a watershed) and generate statistical data. Usually they do not contain unique data but use common global models (such as NOAA, GPCC, and others).

II. The GeoGIPSAR System

The GeoGIPSAR [4] system is a development of the GIPSAR [5] information prognostic system, which was implemented in the late 1990s. It relied on several diverse methods of long-term forecasting (background, estimation, probabilistic, approximate learning) based on a special methodology for generating forecasts of increased reliability, and tools for data analysis and verification.

The GIPSAR system is implemented in the experimental universal programming environment ZIRUS [5] with a flexible model of dynamic typed objects (segments and types of segments) and has been successfully used for a long time to analyze and predict the hydropower potential of various hydropower power plant (HPP) cascades. The ZIRUS environment represents universal mechanisms for the construction and interaction of components with a logical-functional link description language (OLFIS) built into it. The modernization of the GIPSAR system to integrate it with a set of programs for geoclimatic data analysis and processing formed the basis for the modern version of GeoGIPSAR, which makes it possible to study many aspects of the global and regional climate in order to improve the efficiency of methods for long-term forecasting of the hydropower potential and climatic factors affecting the performance of energy systems.

The GeoGIPSAR system uses dynamic objects and

Table 1. The main functions of the GeoGIPSAR and their description

Functions	Description of functions
Time series analysis	Smoothing filters, extreme envelopes (Huang), integral-difference filters, attractors
Wavelet analysis	Waveletograms, spectral characteristics, cross-coherent, discrete analysis
Data samples creation	Spatial, time, aggregation, indices
Geoclimatic data analysis	Aggregation, averaging, visualization methods, indicator distributions, velocity fields
Spatial and time decomposition	Spatial: tributaries, basins, reservoirs; time: year, quarter, month
Calculation of hydropower potential of flow	Statistics analysis, dynamics forecast, verification
Internet monitoring	Information resources, monitoring methodology, integrity support, data verification
Forecasting	Qualitative, probabilistic, learning, astrophysical methods
Search for predictors	Hydrological, meteorological, experimental

a universal data storage (segment database), as well as storage files for multidimensional grid data of a special format (gi3) with various aggregate indicators included in them. The main functions of the system are shown in Fig. 1 and Table 1.

Using the information from world data centers and global forecasting models, the GeoGIPSAR constantly monitors global and regional climate changes and provides various probabilistic forecast estimates of inflows for the studied basins, for example, the Angara-Yenisei cascade of hydroelectric power plants, including the basins of the large rivers such as the Angara and the Yenisei [6, 7]. A set of standard converters and templates for processing various data samples from open sources has been implemented. Sites are periodically polled for updated data, the necessary files are downloaded, converted to the desired format, and sent to the appropriate storage.

III. Basic Data Sets of the GeoGIPSAR

The GeoGIPSAR implements the processing of various data samples from the sources presented below.

NOAA datasets [14] are reanalysis data of the National Oceanic and Atmospheric Administration (the USA). NOAA is engaged in various types of meteorological and geodetic research and forecast, and the study of the world's oceans and atmosphere. It provides the following data services:

- Monitoring and observing Earth systems with instruments and data collection networks;
- Describing Earth systems through the data exploration and analysis;
- Assessing and predicting changes in these systems over time;
- Involving, advising, and informing the public and partner organizations;
- Managing the resources to improve society, the economy, and the environment.

NOAA data are used in reanalysis studies. Reanalysis is a scientific method designed to obtain complete information about how weather and climate change over time. According to this method, the observation data and a numerical model that simulates one or more aspects of the earth system are objectively combined to produce a synthesized estimate of the state of the entire system. The reanalysis usually takes several decades or longer and covers the entire globe from the Earth's surface and to the upper atmosphere. Reanalysis products are widely used in climate research and services, including monitoring and comparing current climate conditions with past conditions, identifying the causes of climate fluctuations and changes, and making climate forecasts.

The site includes the main meteorological indicators for various layers of the atmosphere and stratosphere in daily resolution (temperature, geopotential, indicators of atmospheric circulation, etc.) with a delay of 2–3 days.

GPCC [15–17] is Global Precipitation Climatology Centre (Germany), which houses monthly data for more than 100 years of global precipitation on the surface of the Earth. It employs the data from about 85000 weather stations around the world. The service allows researcher to use operational data with different resolutions on a regular grid (from 0.25° to 2.5°) and a monthly time interval. GPCC provides the following products:

- Climatology 1951–2000 (GPCC_Clim), which is used for application as a reference, for utilization of the anomaly interpolation method, and has high representativeness.
- Full Data Reanalysis (GPCC_FD), which is used for verification of models, analysis of historic global precipitation, or for research into the global water cycle, and has high accuracy.
- Full Data Daily Product (GPCC_FD_D) is recommended to be used when the daily precipitation information is of highest importance.
- Monitoring Product (GPCC_MP) is characterized by high availability and reasonable timeliness, and can be used for satellite data calibration or early annual reporting.
- First Guess Product (GPCC_FG), First Guess Daily Product (GPCC_FG_D), and Drought Index Product (GPCC_DI_M) demonstrate high timeliness and can be used for drought monitoring.

GPCC is the basis for generating precipitation reanalysis data. It also supports regional climate monitoring, model validation, climate variability analysis, and water assessment studies.

Table 2. The Web Service control parameter requirements.

Parameters/Section	Requirements
Basic parameters	Coordinates, month, range of months (when averaged), graph type (precipitation, pressure, temperature, etc.), anomaly search feature
Data visualization	Scale, layer selection, grid adjustment, legend range
Date setting	Current date (for a separate period), start and end dates (for a time interval)
Comparison of average indicators by period	Initial data for processing each period
Analysis of correlation fields	Correlation type (Pearson), series names for correlation
Trend analysis	Correlation type (trend), interval of dates
Index analysis	Graph and data type sets

NOAA National Centers for Environmental Information (NCEI) [18] maintains the archives and provides data on the solar and upper atmosphere, ionosphere and space environment, including observations of the Earth from space. It estimates the daily terrestrial solar UV index and predicts UV levels for the next day.

Pogodaiklimat [19] (Weather and Climate in Russian) is a service with meteorological data for individual points (together with archives), which provides the most complete and prompt monitoring of weather and climate on a global scale. The service presents weather forecasts for most cities in the world, and ensures climate monitoring and climate data, current weather data from all international exchange stations that regularly transmit information about actual weather, weather records, and information about dangerous and extreme events.

CFS [20–22] is a Climate Forecast System model from NOAA National Centers for Environmental Prediction (NCEP). In the context of global and regional climate changes, the use of only hydrometeorological statistics for predictive estimation of water content and temperatures becomes ineffective. Given the significant progress in the creation and development of global climate models over the past decades, it seems appropriate to use them for long-term estimation of water content and other hydrometeorological indicators. One of such models is the global climate model CFSv2. Its simulation results are refined daily in the form of ensemble forecasts of the state of the atmosphere and ocean with a time interval from several hours to ten months for the entire globe. The ensemble approach used in the model makes it possible to generate probabilistic estimates of the state of the atmosphere in the long term.

In addition to these basic data, the GeoGIPSAR also uses regional sources and observational statistics, such as annual river flow data, air temperatures, and others.

IV. Requirements for the basic Web service controls

Along with the development of spatial data processing services as independent GIS resources that provide researchers with tools for visualizing heterogeneous geoclimatic data, it is also of particular importance to create dedicated software for analyzing data for a given territory, basin, time interval, certain indicators, and others. For example, the GeoGIPSAR system components for processing prognostic data ensembles can show the dynamics of changes in prognostic meteorological indicators for any selected cell of grid data and allow setting weighting factors, as well as their spatial distributions.

A draft interface of the GeoGIPSAR has been developed in the form of a dedicated Web service to expand the range of its users.

The Web service requirements include:

- interaction with the GeoGIPSAR through transmission of the parameters and processing of its work results;
- HTML interface with data entry and validation;
- creation of output data templates (graphs, tables, reports);
- visualization of work results;
- differentiation of access to data (multi-user mode).

The Web service implementation features are:

- cross-platform, portability, small (compact) size, and the ability to replace external applications;
- the ability to use external plotting systems for high-quality visualization (Gnuplot [23]) with flexible output templates;
- performance through the use of modern technologies for data processing and output of results (programming languages Lua and PHP);
- reliability and uninterrupted operation (for example, creation of filters to block bots, use of authentication);
- integration with common databases (MySQL).
- *A multi-user mode of operation* is provided using access control in the form of various user groups such as:
- viewer (generates templates and views maps);
- editor (monitors, changes and adds data to the system);
- programmer (creates applications and interfaces);
- GIS-specialist (provides conformity of maps to given requirements, creates extended 2D and 3D maps, visualizes and analyzes them);
- analyst (analyzes the results; examines the data; performs spatial, statistical, and predictive analysis; and searches for relationships and regularities);
- administrator (delimits the rights of access to data and monitors the state of the system).

The considered Web service includes the following basic functions for working with the GeoGIPSAR:

1. Generation of climatic maps of absolute and relative indicators for the selected catchment basin of HPP

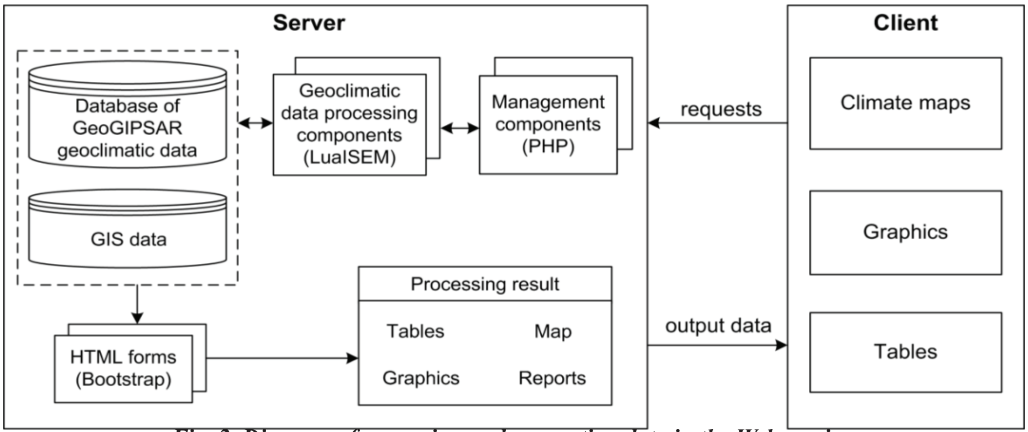


Fig. 2. Diagram of managing and generating data in the Web service.

reservoirs;
2. Analysis of data for a given year with the display of the indicator distributions;
3. Analysis of the indicator differences for the given two periods;
4. Comparison of average indicators for the periods of several years;
5. Analysis of correlation fields (links) for selected time series;
6. Analysis and selection of trends;
7. Analysis of vorticity, humidity, and atmospheric circulation indices.

Table 2 shows the requirements for the Web service control parameters for interaction with GeoGIPSAR.

V. Development Technologies of the Web Service

The Web service implementation relies on the following programming languages, systems, and frameworks.

Lua programming language. Scripting languages, unlike compiled ones, greatly simplify the technology of creating modules, because they need to have only an editor of the text code and debug it through the command line of a file manager or other system tool. The Lua language is unique in its following main properties:

- compactness and portability (the size of a single executable module with dedicated api-functions does not exceed 200 Kb);
- simplicity of syntax combined with powerful tools for using dynamic data (associative tables) and high performance of the implemented algorithms;
- ease of reading and writing text files with advanced processing tools through regular expressions;
- use as a stand-alone program text processor and as an extension of technologies in C/C++ (and other languages);
- the possibility of implementing various programming paradigms (imperative, object-oriented, functional);
- openness of the program code and cross-platform.

Experience of using the Lua language has shown that it can be effectively applied in various aspects (coding of individual algorithms; task launch control; text file conversion, and others). The flexibility, simplicity and efficiency of the language become evident when creating control scripts for controlling other software systems with the code included to organize data exchange between them.

LuaISEM is a Lua language extension developed by the MESI SB RAS by adding applied and basic functions. It contains a set of libraries of functions for processing the data of global climate models, including their downloading, analysis, output templates, and others.

The high-quality graphs are created using a cross-platform portable system Gnuplot [23] with a developed declarative language for their description. Gnuplot allows user to display data both as separate files (it supports many common graphic formats) and interactively in Web scripts.

PHP language is employed to run server-side programs and call Lua functions (LuaISEM). It is used to process the data of forms, generate dynamic pages, and save entered user data and sessions (through cookies technology). One of the PHP advantages is that it supports a wide range of databases and many extensions.

PhpMyAdmin server is used to administer PHP. It supports a wide range of database operations such as MySQL and MariaDB. All operations on them (creating, viewing, and modifying tables, columns, relations, indices, and others) can be performed through the user interface, while the user remains able to directly execute any SQL statement.

RedBeanPHP [24] is a powerful PHP add-on that makes working with databases much easier. It allows exchanging different types of models, in particular, between a data store and a program. It is used to simplify the process of storing objects in a relational database and retrieving them.

Bootstrap [25] is a large collection of easy-to-use code snippets written in HTML, CSS, and JavaScript, which enable developers and designers to quickly create fully responsive websites.

The operation of the considered Web service is implemented as a client-server architecture. The diagram of managing and generating data in the Web service is shown in Fig. 2.

The server block is executed in PHP and includes

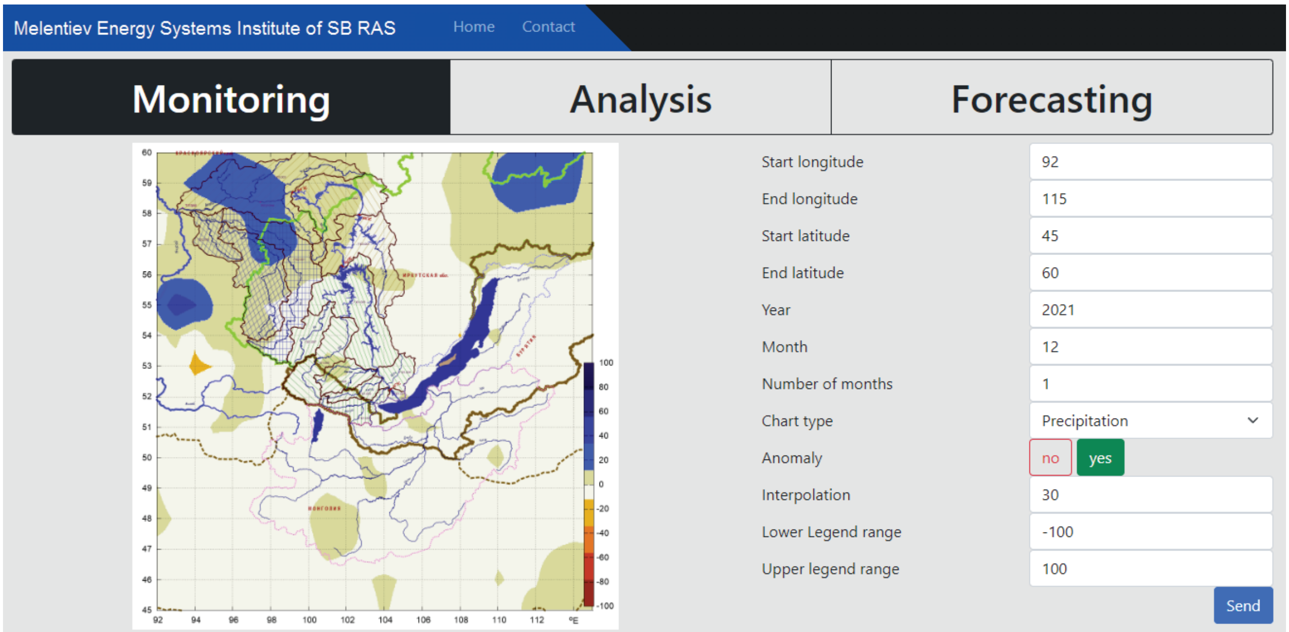


Fig. 3. An example of setting basic parameters for generating climate maps in the Web service.

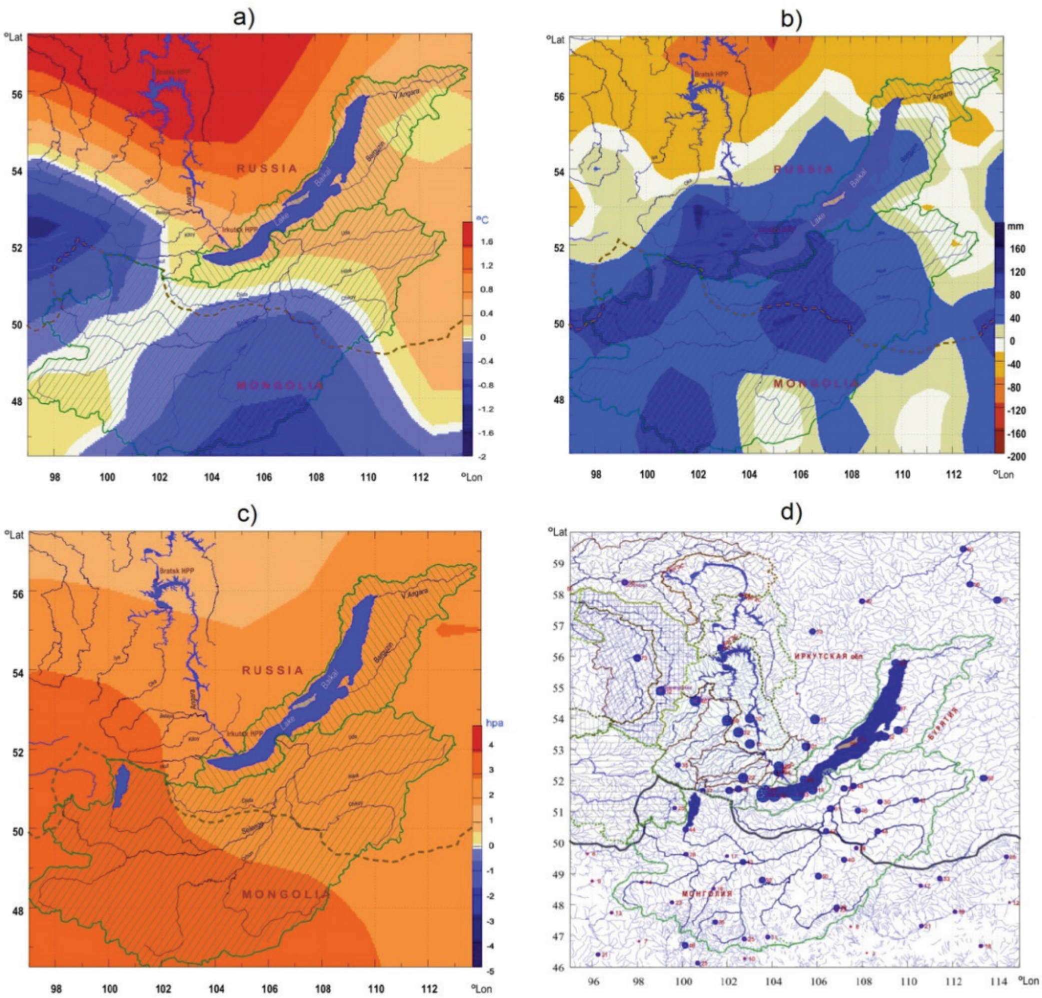


Fig. 4. An example of generating climate maps; search for deviations (anomalies) for the summer period (June-August, 2021) in the Lake Baikal basin: temperature (a), precipitation (b), and pressure (c); meteorological observation points (d).

administration of data access via RedBeanPHP, data updating, parameter and style management, and creation of input/output HTML forms via Bootstrap. Data are processed using the LuaISEM language.

To start working with the system, the user needs to log in or register. Administrator can manage the system by setting up user rights, climate databases, map templates, and others. When the user logs in with the rights of a viewer, editor, GIS specialist or analyst, a set of basic GeoGIPSAR management functions is displayed. Several sections of working with climate data are available (monitoring, analysis, and forecasting).

When the user selects the section with the analysis of climatic data, the form for entering parameters is displayed (Fig. 3). The parameters entered into the form are sent to a script written in LuaISEM. For simplicity, this script replaces the data in the template with the data entered by the user. After the replacement, a working Lua script is launched. This script is connected to the GeoGIPSAR, which processes global climate data and converts them into the required format. The result is the visualization of geoclimatic data in the form of geographic maps of various types (graphs, tables, and reports) (Fig. 4).

The Web service development and management are implemented by: 1) testing a local version; for example, USBWebserver is a lightweight local Web server using Apache, PHP, MySQL and PHPMyAdmin, which allows user to work on various systems without installing it; 2) installing the updated software to a stationary system (server). Local version improves the development speed and reliability.

VI. Conclusion

The Web service is currently actively evolving. Its further development involves the expansion of the system core with the ability to quickly select the forms of data presentation and visualization. It is planned to place the Web service on the websites of the MESI SB RAS (https://isem.irk.ru) and the scientific project for the study of Lake Baikal (http://baikal-project.icc.ru).

Acknowledgements

The research was carried out under State Assignment Project (no. FWEU-2021-0003, reg. number AAAA-A21-121012090014-5) of the Fundamental Research Program of the Russian Federation 2021–2025.

References

[1] N. V. Abasov, V. M. Nikitin, E. N. Osipchuk, "A System of Models to Study Long-Term Operation of Hydropower Plants in the Angara Cascade," *Energy Systems Research*, vol. 2, no. 6, pp. 5–18, 2019.

[2] V. M. Nikitin, N. V. Abasov, E. N. Osipchuk, "Modeling of Long-term Operating Regimes of Hydro Power Plants as Part of Energy and Water Systems in the Context of Uncertainty," *E3S Web of Conf.*, vol. 209, pp. 7, 2020.

[3] T. V. Berezhnykh, N. V. Abasov, "The increasing role of long-term forecasting of natural factors in energy system management," *Intern. Journal of Global Energy*, vol. 20, no. 4, pp. 353–363, 2003.

[4] N. V. Abasov, "The GeoGIPSAR system of long-term forecasting and analysis of environment-related factors of the energy industry," in *Proc. of the International Meeting of APN: Extreme manifestations of global climate change in North Asia Enviromis-2012*, Irkutsk, Russia, 2012, pp. 63–66. (In Russian)

[5] N. V. Abasov, T. V. Berezhnyh, A. P. Reznikov, "Long-term forecast of environment-related factors of the energy industry in the information-forecasting system GIPSAR," *Proceedings of the Russian Academy of Sciences, Power Engineering*, vol. 6, pp. 22–30, 2000. [In Russian]

[6] V. M Nikitin, N. V. Abasov, T. V. Berezhnikh, E. N. Osipchuk, "The Angara-Yenisei HPP cascade under a changing climate," *Energy Policy*, vol. 4, pp, 62–71, 2017. (In Russian)

[7] E. N. Osipchuk, V. M. Nikitin, N. V. Abasov, "Possibilities of enhancing the efficiency of the Angara cascade of hydroelectric power plants," *Journal of Physics: Conf. Series*, vol. 1652, p. 012022, 2020.

[8] Ventusky Wind, Rain and Temperature Maps [online]. Available: https://ventusky.com. Accessed on May 10, 2022.

[9] Earth Nullschool A Global Map of Wind, Weather, and Ocean Conditions [online]. Available: https://earth.nullschool.net. Accessed on May 10, 2022.

[10] Windy Wind map and weather forecast [online]. Available: https://windy.com. Accessed on May 10, 2022.

[11] EarthAtlas – Mapping System for Earth Sciences Data, Geographic Projection, Global Extent, etc. [online]. Available: https://earthatlas.sr.unh.edu. Accessed on May 10, 2022.

[12] Meteologix Swiss Quality Weather Forecasting [online]. Available: https://meteologix.com. Accessed on May 10, 2022.

[13] Lobelia.Earth Lobelia past climate explorer [online]. Available: https://era5.lobelia.earth. Accessed on: May 10, 2022.

[14] F. Hourdin, T. Mauritsen, A. Gettelman, at el, "The art and science of climate model tuning," *Bull. of the Am. Meteorol. Soc.*, vol. 98, no. 3, pp. 589–602, 2017.

[15] A. Becker, P. Finger, A. Meyer-Christoffer, B. Rudolf, K. Schamm, U. Schneider, M. Ziese, "A description of the global land-surface precipitation data products of the global precipitation climatology centre with sample applications including centennial (trend) analysis from 1901–present," *Earth Syst. Sci. Data*, vol. 5, pp. 71–99, 2013.

[16] K. Schamm, M. Ziese, A. Becker, P. Finger, A. Meyer-Christoffer, U. Schneider, M. Schröder, P. Stender, "Global gridded precipitation over land: A description

of the new GPCC First Guess Daily product," *Earth Syst. Sci. Data*, vol. 6, pp. 49–60, 2014.

[17] U. Schneider, P. Finger, A. Meyer-Christoffer, E. Rustemeier, M. Ziese, A. Becker, "Evaluating the hydrological cycle over land using the newly-corrected precipitation climatology from the global precipitation climatology center (GPCC)," *Atmosphere*, vol. 8, no. 3, p. 52, 2017.

[18] NOAA Solar Databases for Global Change Models [online]. Available: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA. Accessed on May 10, 2022.

[19] Weather news, Weather forecasts, Climate monitor, World climate, Weather archives, etc. [online] Available: http://www.pogodaiklimat.ru. Accessed on May 10, 2022. (In Russian)

[20] X. Yuan, E. Wood, L. Luo, M. Pan, "A first look at climate forecast system version 2 (CFSv2) for hydrological seasonal prediction", *Geophysical research letters*, vol. 38, no. 13, Art. no. L13402, 2011.

[21] A. Rai, S. K. Saha, "Evaluation of energy fluxes in the NCEP climate forecast system version 2.0 (CFSv2)," *Clim. Dyn.*, vol. 50, pp. 101–114, 2018.

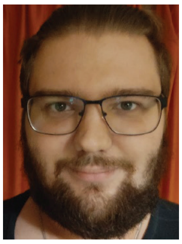
[22] S. Saha, S. Moorthi, X. Wu, et al, "The NCEP Climate Forecast System Version 2," *Journal of Climate*, vol. 27, no. 6, pp. 2185–2208, 2014.

[23] P. K. Janert, *Gnuplot in Action: Understanding data with graphs*, 2nd ed. Manning Publications, 2016, 400 p.

[24] RedBeanPHP Easy ORM for PHP [online]. Available: https://redbeanphp.com. Accessed on May 10, 2022.

[25] Bootstrap The most popular HTML, CSS, and JS library in the world [online]. Available: https://getbootstrap.com. Accessed on May 10, 2022.

Evgeny Osipchuk, Ph.D., graduated from the Institute of Information Technologies and Modeling at Irkutsk State Transport University as a software engineer (2009). Currently he is a researcher at Hydropower and Water Management Systems Laboratory of the Melentiev Energy Systems Institute of SB RAS. His research interests are application of long-term inflow forecasts for modeling HPP operating conditions with various water and energy constraints.



Viktor Gasan received a degree in Applied Informatics in Economics from the College of Baikal State University (2018) and a degree in Information Systems from Irkutsk State Transport University (2022). His research interests include the web-development, and geoclimatic analytics.

Ignition of a Cold Pulverized Coal Fuel by Means of an Electric Ignition System

D. S. Sinelnikov[1,2*]

[1]Novosibirsk State Technical University, 20 K. Marx Ave., Novosibirsk, 630073, Russia
[2]Siberian Energy Solutions LLC, Of. 317, 1/1 Dimitrov Ave., Novosibirsk, 630004, Russia

Abstract — **Coal-fired generation has long been, and still is, one of the leaders in global electricity generation. The high share of coal-fired generation in the global energy mix is achieved due to the known advantages of this fuel, including high availability of reserves, relative ease of extraction, and the possibilities of providing its reserves at the plants and reliable equipment operation even in the event of fuel supply interruptions. Coal combustion in modern industry requires the development of modern start-up systems for coal-fired boiler units without the use of fuel oil. Fuel oil is used for starting up boilers and maintaining the flame during transient conditions or at low loads of boiler. At the same time, the use of fuel oil has some disadvantages, both technical and environmental. The greatest challenge in developing high-frequency ignition systems is to understand the chemical kinetics processes for the plasma chemical reaction of fuel mixture ignition. This paper presents experimental and industrial studies on the application of an electric ignition system for coal fuel based on a high-frequency power source. Experimental studies were carried out on a laboratory bench with a thermal capacity of 5 MW. Industrial tests were performed at the operating enterprises of the power sector of the Russian Federation. Lignite and hard coals of different thermal-technical composition were used as fuel samples. The principle behind the effect of this system on the fuel ignition has been shown.**

Index Terms: **coal-fired generation, experiment, principle of operation, electric ignition, ignition, oil-free ignition, ecology, efficiency, economy, experience, lignite, hard coal, low-grade fuel.**

* Corresponding author.
E-mail: sinelnikov.2011@stud.nstu.ru

http://dx.doi.org/10.38028/esr.2022.03.0002
Received September 13, 2022. Revised September 21, 2022.
Accepted September 30, 2022. Available online December 5, 2022.

I. Introduction

Every year, more than 5 million tons of fuel oil are burnt in the Russian Federation to maintain the combustion of pulverized coal in boilers, and since the quality of steam coal declines, more fuel oil is required [1]. Firing up the power boiler needs on average 60–80 t of fuel oil (at its average cost of ~ 15 thousand rubles/ton). One of the important directions for the development of generating companies in the Russian Federation is to increase the economic efficiency and environmental friendliness of the production cycle.

Combustion of coal fuel in the modern industry requires the development of modern systems of starting up coal-fired boiler units without the use of fuel oil [2, 3]. Fuel oil is used for starting up boilers and maintaining the combustion flame in transient conditions or at low loads of a boiler [4]. However, the use of fuel oil has some drawbacks, both technical and environmental [5]. The greatest challenge in the development of high-frequency ignition systems is to understand the processes of chemical kinetics for the plasma-chemical reaction of the fuel mixture ignition.

This study aims to investigate this process.

The potential for the development of electric ignition technology is to reduce the use of fuel oil at the coal-fired power plants in Russia and abroad, to partially or completely convert the plants to oil-free operation, and reduce the costs of maintaining the fuel oil facilities. Abandoning fuel oil at coal-fired thermal power plants (TPPs) will reduce the environmental impact of coal-fired generation, and given the hundreds of pulverized coal-fired boilers, it will affect the environmental situation in Russia.

It is also worth noting that it is possible to save other highly reactive fuels at the plant, which are used to stabilize pulverized coal flare and to start up the boilers. The use of electrically ignited coal for these purposes is, on average, 2 times cheaper than the use of natural gas. Replacement of the highly reactive fuel with coal will reduce the auxiliary fuel consumption of the plant, thereby providing additional profits.

II. Electric Ignition System

A team of authors from Siberian Energy Solutions LLC together with Zio-Energy LLC supported by Novosibirsk

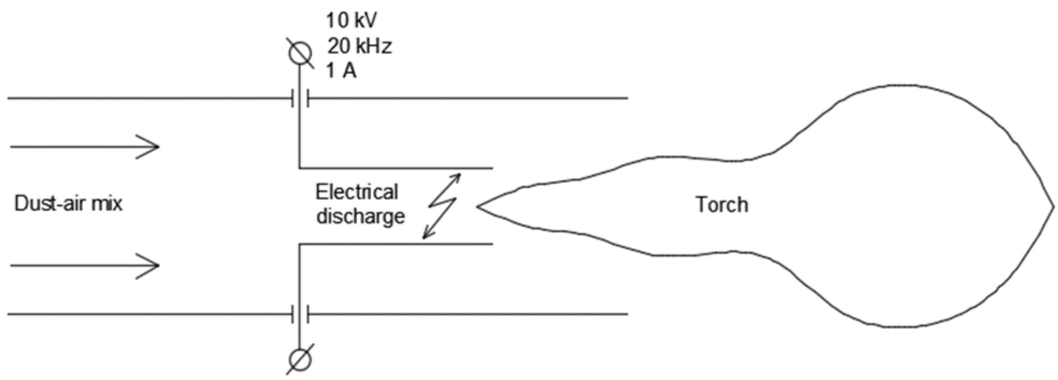


Fig. 1. The operating principle of electric ignition system.

Table 1. Coal characteristics ensuring high performance of the electric ignition technology.

Name	Coal characteristics	Coal dust characteristics
Irsha-Borodinsky brown coal	Qir = 3 880 kcal/kg; Wr = 32.6%; Ar = 5.66%; Vdaf = 48.0%.	R90 = 72.9%; R200 = 21.4%
A mixture of Azeisky, Mugunsky, Golovinsky, Cheremkhovsky, and Irbeisky brown coals:	Qir = 4 000 kcal/kg; Wr = 21.5%; Ar = 17.8%; Vdaf = 48.3%.	R90 = 49.2%; R200 = 11.2%
A mixture of Azeisky and Mugunsky brown coals:	Qir = 3 740 kcal/kg; Wr = 25.8%; Ar = 16.3%; Vdaf = 46.5%.	R90 = 45.0…55.0%
Kuznetsk Basin coal of grades G (gas) and D (long-flame)	Qir = 5 600 kcal/kg; Wr = 15.3%; Ar = 8.2%; Vdaf = 39.8%.	R90 = 20…25%
Ekibastuz KSN coal, Bogatyr mine (with additional power supply)	Qir = 3 990 kcal/kg; Wr = 5.0%; Ar = 40.3%; Vdaf = 31.6%.	R90 = 10…15%

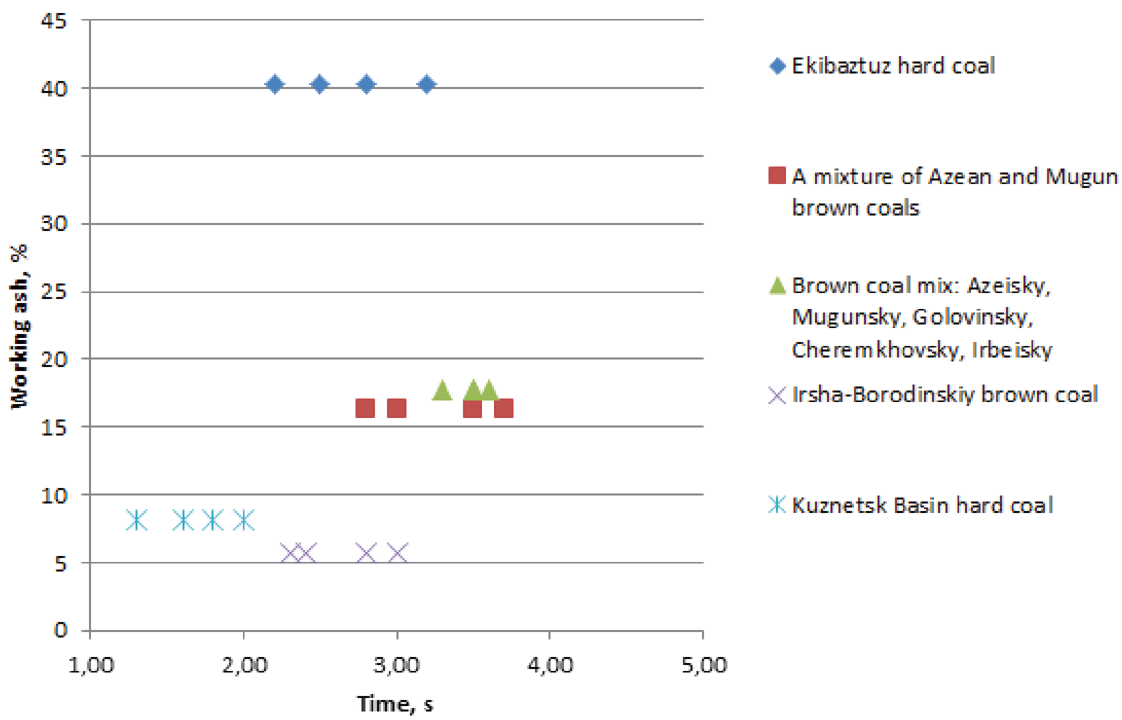


Figure 2. Ignition delay time for coal samples exposed to an electrical ignition system.

State Technical University and Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences developed a technology of electric ignition. The first patent was received by Novosibirsk developers in 2009 [6].

The operating principle of this technology is shown in Fig. 1. Electric current applied to cylindrical electrodes has the following parameters: voltage 3–10 kV, frequency 18–22 kHz, and rated current strength 1A. As a result, a high-frequency breakdown occurs in the interelectrode space. Electric field strength in the interelectrode space is 0.3–1 kV/cm. A coal-air mixture is then fed into the interelectrode space, which results in the ignition of the mixture. One of the advantages of the power supply used is the input voltage of 380 V, which allows the power supply to be used without additional electrical equipment and guarantees electromagnetic compatibility with the auxiliary networks of thermal power plants.

The efficiency of this technology has been confirmed at the industrial facilities and by the laboratory tests using coal with the parameters presented in Table 1. The experience gained until now in the use of electric ignition systems allows switching to oil-free combustion of pulverized coal and excluding the use of fuel oil facilities of coal-fired plants (for coal with an ash content less than 20–25%).

Based on the experiments carried out at the firing bench of the Institute of Thermal Physics of SB RAS (Novosibirsk) with a thermal capacity of 5 MW and industrial tests of the technology, the following relationships between ignition delay time and ash content (Fig. 2) were obtained for the cold fuel with the characteristics presented in Table 1. The ignition of Ekibastuz coal in cold state failed, which can be explained by the high ash content. The ignition delay time for this coal is given after warming up the burner with Irsha-Borodinsky lignite to the temperature of about 400 °C.

The following processes can explain the principle behind the effect of this technology on ignition:

- Thermal ignition by electrical discharge (the discharge temperature reaches 7000 K [7]). This effect is localised and confined to the breakdown area of the interelectrode space. Once in this area, the carbon particles experience a thermal shock, which leads to their rapid heating and the release of volatile components. The interaction of coke residue with plasma leads to sublimation of carbon and its interaction with oxygen C + O = CO, which proceeds homogeneously. When exposed to high temperatures, the oxygen-containing groups break down releasing CO, CO_2, H_2O [8, 9].
- High-frequency electric field has an advantage over the constant electric field. Experimental work [10] shows that starting with a frequency of 150 Hz at a voltage of 1 kV, high-frequency electric field leads to a marked increase in the flame velocity compared to the constant electric field.
- Under the influence of high voltage electric field, fuel atoms transition to an excited state (electrochemical effect). The electrochemical effect produces high velocity electrons, radicals, ions, and excited molecules in the pre-flame zone, which directly change the chemical composition of the flame [11–15].

The latter thesis can be generalized to the theory of active center formation [16]:

$$q \approx pQ\sqrt{wa}\,, \tag{1}$$

where q is the amount of heat released by the reaction; p is the reacting mixture density; Q is heat of fuel combustion; w is reaction rate; a is temperature conductivity of fuel.

According to Semenov's theory of chain reactions [17], the rate of a stationary reaction is

$$w = \frac{\delta \nu_1^2}{2\nu_2^0}\left(\sqrt{1+\frac{4w_0\nu_2^0}{\delta_1^2\nu_1^2}}+1\right), \tag{2}$$

where w_0 is the rate of active centers generation; δ is the probability of chain branching; ν is an average length of the respective process chain.

Under the assumption that the rate of active centers generation is a function of the electric field strength

$$\Delta w_0 = f(E/p), \tag{3}$$

the application of an electric field to the reaction region results in its acceleration.

Reduction in ignition temperature was recorded by Kuzmin [18], who studied ignition temperature of luminous gases under the influence of electrostatic discharge.

III. Conclusion

An electric ignition technology, which implements a thermoelectric ignition mechanism, has been developed and tested for the combustion of hard coal and lignite. This technology makes it possible to achieve stable ignition of pulverized coal within 2–4 seconds after feeding into the burner. The application of this technology to intensify the ignition of a pulverized coal flare creates additional possibilities for fuel oil-free ignition and the economical and environmentally friendly combustion of various coals. The possibility of ignition (with additional power supply) for Ekibastuz coal with an ash content of 40% should be mentioned separately. The ignition delay time for this coal is given after warming up the burner with Irsha-Borodinsky lignite to the temperature of about 450 °C and makes up about 3 seconds. The energy input for ignition is less than 1% of thermal output of the burner for lignite and 2–3% for high-ash hard coal (including preheating). The industrial tests of the burner equipped with electric ignition technology using Ekibastuz coals are planned to be carried out in 2023.

Acknowledgments

The research was carried out with financial support as part of the NSTU development programme, research project no. C22-24

References

[1] V. N. Yelin, "Technology of plasma ignition and maintaining combustion in pulverized coal boilers," *Ugol*, vol. 4, no. 1020, pp. 12–13, 2011. (In Russian)

[2] E. R. Zvereva, "Utilization of Carbonate Sludge from Chemical Water Treatment Systems of Thermal Power Plants," *Bulletin of Kazan State Energy University*, vol. 4, no. 11, pp. 26–35, 2011. (In Russian)

[3] V. A. Pinchuk, T. A. Sharabura, A. V. Kuzmin, "The effect of water phase content incoal-water fuel on regularities of the fuel ignition and combustion," *Fuel Process.Technol.*, vol. 191, pp. 129–137, 2019. DOI: 10.1016/j.fuproc.2019.04.011.

[4] D. T. Pio, L. A. C. Tarelho, T. F. V. Nunes, M. F. Baptista, M. A. A. Matos, "Co-combustion of residual forest biomass and sludge in a pilot-scale bubbling fluidized bed," *J. Clean. Prod.*, vol. 249, pp. 119309, 2020. DOI: 10.1016/j.jclepro.2019.119309.

[5] V. Messerle, A. Ustimenko, O. Lavrichshev, "Plasma-fuel systems for clean coal technologies," *Proc. Inst. Civ. Eng*., vol. 174, no. 2, pp. 79–83, 2021. DOI: 10.1680/ jener.19.00053.

[6] Yu. I. Naumov, "Device for plasma ignition of pulverized coal fuel," RU Patent 2410603, Nov. 17, 2009. (In Russian)

[7] D. A. Yagodnikov, A. V. Voronetskiy, "Influence of external electric field on peculiarities of ignition and combustion processes," *Physics of Combustion and Explosion*, vol. 30, no. 3, pp. 3–12, 1994. (In Russian)

[8] M. A. Malik, "Synergetic effect of plasmacatalyst and ozone in pulsed corona discharge reactor on the decomposition of organic pollutants in water," *Plasma Sources Sci. Technol.*, vol. 12, no 4, pp. 26–32, 2003.

[9] L. S. Polak, A. A. Ovsyannikov, D. I. Slovetsky, F. B. Vurzel, *Theoretical and Applied Plasma Chemistry*. Moscow, Russia: Nauka, 1975, 375 p. (In Russian)

[10] A. F. Garanin, P. K. Tret'yakov, A. V. Tupikin, "Effect of constant and pulsed-periodic electric fields on combustion of a propane-air mixture," *Combustion, Explosion, and Shock Waves*, vol. 44, no. 1, pp. 18–21, 2008. DOI: 10.1007/s10573-008-0003-3.

[11] T. Ombrello, S. H. Won, Y. Ju, S. Williams, "Flame propagation enhancement by plasma excitation of oxygen. Part I: Effects of O3," *Combust Flame*, vol. 157, no. 10, pp. 1906–1915, 2010.

[12] T. Ombrello, S. H. Won, Y. Ju, S. Williams, "Flame propagation enhancement by plasma excitation of oxygen. Part II: Effects of O2 (a1Dg)," *Combust Flame*, vol. 157, no. 10, pp. 1916–1928, 2010.

[13] W. T. Sun, M. Uddi, T. Ombrello, S. H. Won, C. Carter, Y. G. Ju, "Effects of non-equilibrium plasma discharge on counterflow diffusion flame extinction," *Proc. Combust. Inst*., vol. 33, no. 2, pp. 3211–3218, 2011.

[14] W. Sun, M. Uddi, S. H. Won, T. Ombrello, C. Carter, Y. Ju, "Kinetic effects of non-equilibrium plasma-assisted methane oxidation on diffusion flame extinction limits," *Combust. Flame*, vol. 159, no. 1, pp. 221–229, 2012.

[15] Y. N. Shebeko, "The Effect of an Alternating Electric Field on the Normal Rate of Burning of Organic Compounds," *Physics of Combustion and Explosion*, vol. 4, pp. 48–50, 1982. (In Russian)

[16] E. M. Stepanov, B. G. D'yachkov, *Ionization in the flame and electric field*. Moscow, Russia: Metallurgy Publishers, 1968, 312 p. (In Russian)

[17] N. N. Semenov, *Chain reactions*. Moscow, Russia: Goskhimtekhizdat, 1934, 555 p. (In Russian)

[18] M. A. Kuzmin, *Calculation and design of inertialess furnaces*. Moscow, Russia: Mashgiz, 1961, 356 p. (In Russian)

Thermodynamic Assessment of the Influence of Syngas Composition on Characteristics of Solid Oxide Fuel Cell

I.G. Donskoy*

Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — A mathematical model is proposed to calculate the characteristics of a high-temperature solid oxide fuel cell running on combustible gases obtained by thermochemical conversion of plant biomass. The calculations rely on the approximation of thermodynamic equilibrium for the reacting mixture and the polarization equations recommended in the literature. The proposed mathematical model is used to assess the influence of the produced gas composition (obtained under different conditions) on fuel cell performance. The study has identified the gasification conditions which allow producing syngas whose electrochemical conversion is the most efficient.**

***Index Terms*: mathematical model, fuel cell, high-temperature solid oxide, thermodynamic equilibrium, polarization equations, syngas.**

Introduction

Fuel cells combined with gasification unit can significantly increase the biomass-to-electricity conversion efficiency. In this case, however, gas needs to be cleaned not only from tar and solid particles, but also from sulfur and nitrogen compounds. For example, in [1], the calculated efficiency of a power plant with a fuel cell and an organic Rankine cycle using the exhaust gases achieved almost 55%. In [2], the integration of a Stirling engine and a fuel cell yielded the efficiency of about 40% (with the optimal gas distribution). With a fuel cell used without engines, the estimated efficiency of electricity production was 30% [3-6]. A three-day experiment on a fuel cell operating on syngas obtained by staged gasification of biofuels showed the cell efficiency of about 40% [7].

The assessment of the technical and economic efficiency requires that the dependence of the fuel cell characteristics on the operating conditions, including the fuel gas composition, be known. In the biomass gasification, the gas composition normally depends on the specific air flow rate, process temperature, and fuel moisture. The reactor operation is usually accompanied by natural fluctuations in the flow and temperature parameters (associated with the operation of compressors, granular bed motion, and porous fluid flow), which also affect the composition of the produced gas. In this regard, it is of interest to study the characteristics of the combined operation of a fuel cell and a gasifier.

I. Thermodynamic Model

The theoretical cell potential can be easily estimated through the Gibbs energy change in an electrochemical reaction. However, in real-world devices, the reaction is accompanied by Ohmic and polarization losses. Formulas for the calculation of these losses are proposed in [3, 8].

Consider the oxidation of generator gas that contains CO, H_2, CH_4, CO_2, H_2O, N_2 (the other components are assumed to be removed at the gas cleaning stage). The oxidizing agent is atmospheric oxygen. Then, with the known final composition of the products, the equilibrium cell potential can be calculated:

$$E^0 = -\frac{\Delta G}{nF},$$

where n is the number of electrons transferred in electrochemical reaction (defined as an average number of electrons per one molecule of fuel mixture), F is Faraday constant, ΔG is a Gibbs energy change resulting from the conversion of reagents into oxidation products. The value of ΔG is calculated using thermodynamic data [9].

The real cell potential can be determined using semi-empirical formulas [3, 8]:

$$E = E^0 - \chi\,(I).$$

Here χ is the sum of losses, I is the current density. Usually, the dependence of E on I has a long linear range due to ohmic resistance. When the potential difference is obtained, the useful power can be calculated by the simple formula:

* Corresponding author.
E-mail: donskoy.chem@mail.ru

http://dx.doi.org/10.38028/esr.2022.03.0003
Received September 16, 2022. Revised September 18, 2022.
Accepted September 28, 2022. Available online December 5, 2022.

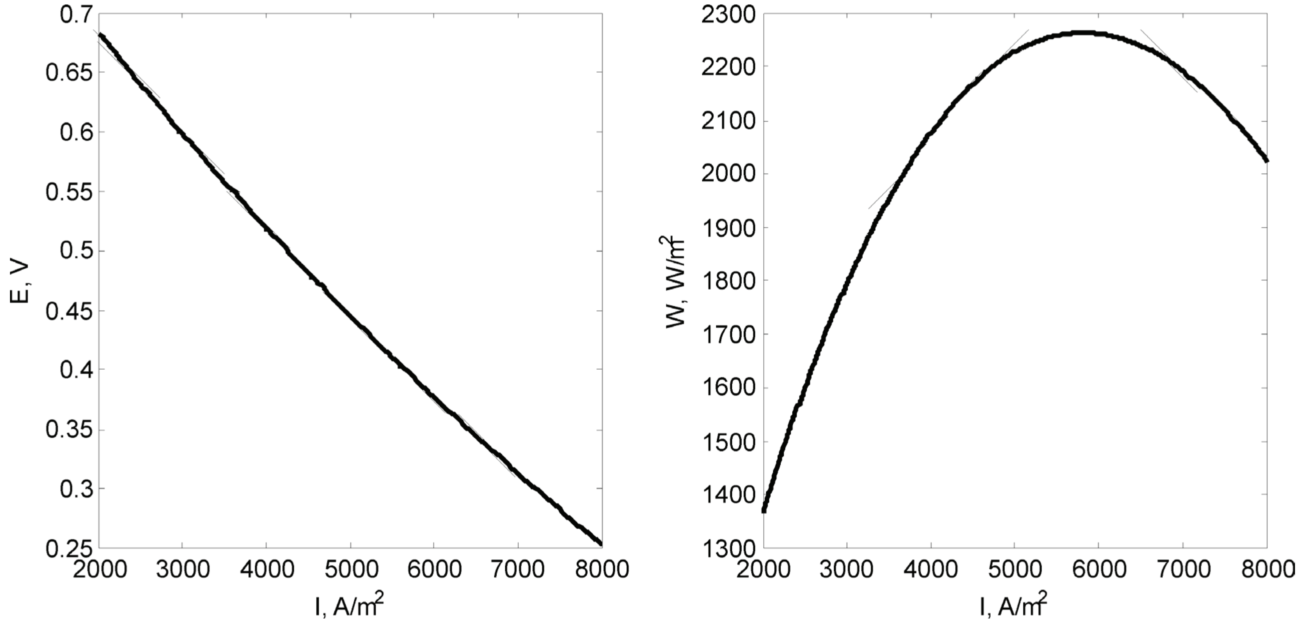


Fig. 1. The dependences of cell potential and power production of the fuel cell on the current density for the gas consisting of CO (20%), H_2 (20%), CO_2 (14%), H_2O (3%), N_2 (43%) (1073 K, 1 atm).

TABLE 1. Gas composition variants, %

No.	Reference	Conditions	CO	H_2	CH_4	CO_2	N_2
1	[12]	steam, entrained flow	40.0	20.0	10.0	30.0	0.0
2	[13]	air/steam, entrained flow	15.0	10.0	5.0	10.0	60.0
3	[14]	air/steam, quartz tube	14.7	12.6	2.0	14.2	56.5
4	[15]	oxygen, fluidized bed	27.5	30.0	5.0	27.5	10.0
5	[16]	steam, quartz tube	15.0	32.0	4.0	49.0	0.0
6	[17]	air, downdraft	20.0	15.0	2.0	10.0	53.0

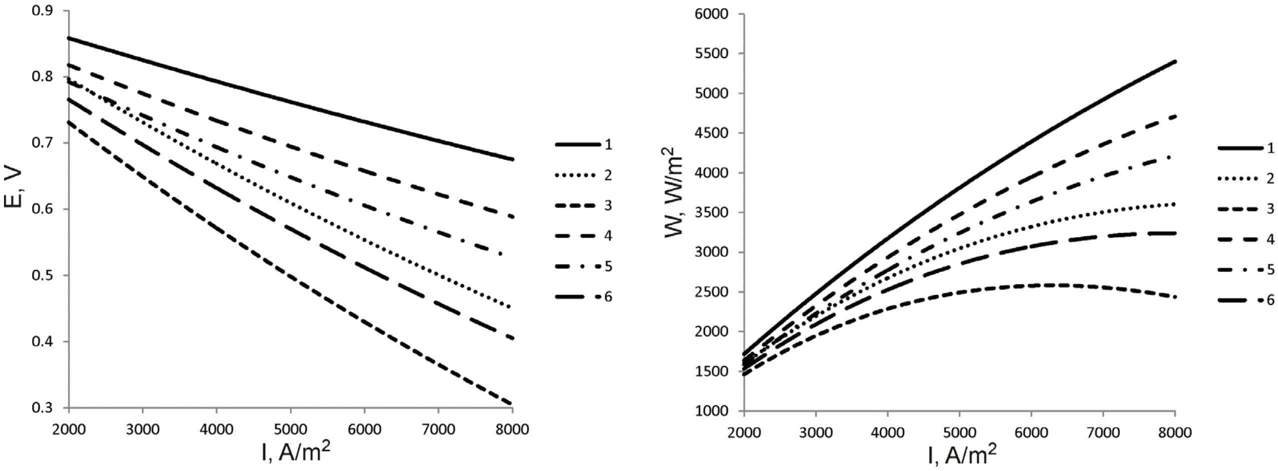


Fig. 2. Dependence of cell potential and power production on fuel gas composition (1073 K, 1 atm).

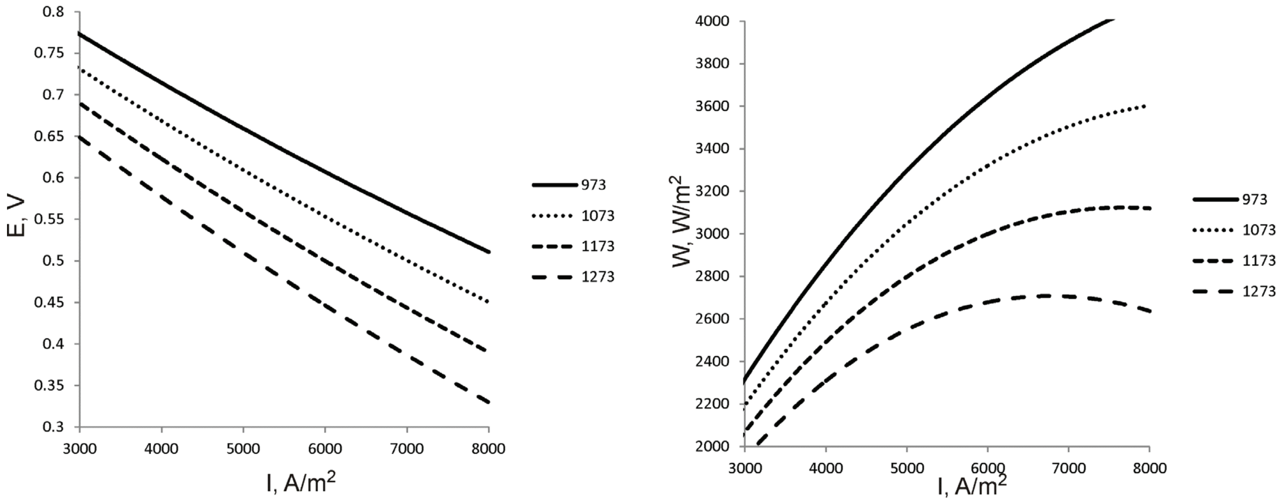


Fig. 3. Dependence of cell potential and power production on temperature for gas composition No. 2, Table 1, (1 atm).

$$W = IE.$$

Calculated dependences of cell potential and power production on current density are presented in Fig. 1.

II. Influence of Fuel Gas Composition

The study presented in [10] examined the solid oxide fuel cell (SOFC) characteristics for different variants of composition of biogas, which contained 50-60% vol. of hydrogen. For the purposes of the present research, several experimental variants of syngas composition were selected. The variants of gas composition are presented in Table 1.

Characteristics of the fuel cell operating on the gases given in Table 1 are shown in Fig. 2. Calculations were carried out for dry gases (pre-treatment is assumed to imply sufficiently deep cooling for water vapor to condense). The composition obtained during steam gasification showed the highest efficiency (in this case, the hydrogen content in the produced gas increases). The air added to the blast in all cases reduces the fuel cell performance, but stabilizes the gasification process and simplifies the gas purification (as pointed out in [11], allothermal gasification is usually accompanied by high tar yield). It can be assumed that there is an optimal air flow rate that allows maintaining the autothermal mode of biomass gasification with the least possible losses.

Additional calculations were carried out for the composition from [16] to evaluate the effect of temperature of the fuel cell on its characteristics. Figure 3 shows that an increase in temperature has a negative effect on the efficiency of the electrochemical conversion. This result may be interesting for thermal management of fuel cells [18]. Note that the model does not take into account the kinetics of oxidation reactions, and the fuel gas conversion is considered complete even at low temperatures, which is why the calculated patterns may show an incorrect dependence of the efficiency on current density in the low-temperature range.

III. Conclusion

The paper proposes a model of a fuel cell, which makes it possible to study the influence of the composition of syngas on its characteristics. Calculations indicate that the highest efficiency of electrochemical conversion is observed for the gas produced by steam gasification of biomass.

Acknowledgment

This work is financially supported by an international collaborative project (BRICS2019-040) under the BRICS STI Framework Programme with government funding organizations of Brazil CNPq (402849/2019-1), Russia RFBR (19-58-80016), India DST (CRG/2018/004610, DST/TDT/ TDP-011/2017), China MOST (2018YFE0183600), and South Africa NRF (BRIC190321424123) using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] L. Pierobon, M. Rokni, U. Larsen, F. Haglind, "Thermodynamic analysis of an integrated gasification solid oxide fuel cell plant combined with an organic Rankine cycle," *Renewable Energy*, vol. 60, pp. 226–234, 2013. DOI: 10.1016/j.renene.2013.05.021.

[2] M. Rokni, "Biomass gasification integrated with a solid oxide fuel cell and Stirling engine," *Energy*, vol. 77, pp. 6–18, 2014. DOI: 10.1016/j.energy.2014.01.078.

[3] W. Doherty, A. Reynolds, D. Kennedy, "Computer simulation of a biomass gasification-solid oxide fuel cell power system using Aspen Plus," *Energy*, vol. 35, no. 12, pp. 4545–4555, 2010. DOI: 10.1016/j.energy.2010.04.051.

[4] M. Morandin, F. Marechal, S. Giacomini, "Synthesis and thermo-economic design optimization of wood-gasifier-SOFC systems for small scale applications," *Biomass and Bioenergy*, vol. 49, pp. 299–314, 2013. DOI: 10.1016/j.biombioe.2013.01.003.

[5] A. Fernandes, J. Brabandt, O. Posdziech, A. Saadabadi, M. Recalde, L. Fan, E. O. Promes, M. Liu, T. Woudstra, P. V. Aravind, "Design, Construction, and Testing of a Gasifier-Specific Solid Oxide Fuel Cell System," *Energies*, vol. 11, no. 8, pp. 1985–2001, 2018. DOI: 10.3390/en11081985.

[6] A. Habibollahzade, M. A. Rosen, "Syngas-fueled solid oxide fuel cell functionality improvement through appropriate feedstock selection and multi-criteria optimization using Air/O2-enriched-air gasification agents," *Applied Energy*, vol. 286, p. 116497, 2012. DOI: 10.1016/j.apenergy.2021.116497.

[7] R. O. Gadsboll, J. Thomsen, C. Bang-Moller, J. Ahrenfeldt, U. B. Henriksen, "Solid oxide fuel cells powered by biomass gasification for high efficiency power generation," *Energy*, vol. 131, pp. 198–206, 2017. DOI: 10.1016/j.energy.2017.05.044.

[8] S. H. Chan, K. A. Khor, Z. T. Xia, "A complete polarization model of a solid oxide fuel cell and its sensitivity to the change of cell component thickness," *Journal of Power Sources*, vol. 93, no. 1–2, pp. 130–140, 2001. DOI: 10.1016/S0378-7753(00)00556-5.

[9] V. P. Glushko, L. V. Gurvich, *Thermodynamic properties of individual substances: vol. 1*. New York, NY, USA: Hemisphere Publishing, 1988.

[10] H. Shi, Q. Li, W. Tan, H. Qiu, C. Su, "Solid oxide fuel cells in combination with biomass gasification for electric power generation," *Chinese Journal of Chemical Engineering*, vol. 28, no. 4, pp. 1156–1161, 2020. DOI: 10.1016/j.cjche.2020.01.018.

[11] A. V. Keiko, D. A. Svishchev, A. N. Kozlov, *Low-grade fuel gasification: state of the art and promising technologies*. Irkutsk, Russia: ESI SB RAS, 2007. [In Russian]

[12] J. J. Hernandez, G. Aranda, J. Barba, J. M. Mendoza, "Effect of steam content in the air–steam flow on biomass entrained flow gasification," *Fuel Processing Technology*, vol. 99, pp. 43–55, 2012. DOI: 10.1016/j.fuproc.2012.01.030.

[13] N. Kobayashi, M. Tanaka, G. Piao, J. Kobayashi, S. Hatano, Y. Itaya, S. Mori, "High temperature air-blown woody biomass gasification model for the estimation of an entrained down-flow gasifier," *Waste Management*, vol. 29, pp. 245–251, 2009. DOI: 10.1016/j.wasman.2008.04.014.

[14] D. C. Le, S. T. Kolaczkowski, D. W. J. McClynomt, "Using quadrupole mass spectrometry for on-line gas analysis – Gasification of biomass and refuse derived fuel," *Fuel*, vol. 139, pp. 337–345, 2015. DOI: 10.1016/j.fuel.2014.09.010.

[15] J. Recari, C. Berrueco, S. Abello, D. Montane, X. Farriol, "Gasification of two solid recovered fuels (SRFs) in a lab-scale fluidized bed reactor: Influence of experimental conditions on process performance and release of HCl, H_2S, HCN and NH_3," *Fuel Processing Technology*, vol. 142, pp. 107–114, 2016. DOI: 10.1016/j.fuproc.2015.10.006.

[16] R. E. Yakovenko, V. B. I'lin, G. B. Narochnyi, A. F. Zubenko, A. A. Savost'yanov, A. L. Lapidus, "Production of Motor Fuel Hydrocarbon Fractions from Pine Wood (Short Communication)," *Solid Fuel Chemistry*, vol. 53, pp. 239–240, 2019. DOI: 10.3103/S0361521919040116.

[17] E. Elsner, M. Wysocki, P. Niegodajew, R. Borecki, "Experimental and economic study of small-scale CHP installation equipped with downdraft gasifier and internal combustion engine," *Applied Energy*, vol. 202, pp. 213–227, 2017. DOI: 10.1016/j.apenergy.2017.05.148.

[18] M. Kozlova, V. Shamansky, "Using dynamic graphs on the example of calculating the temperature field of a lead-acid battery," *E3S Web of Conferences*, vol. 289, p. 06002, 2021. DOI: 10.1051/e3sconf/202128906002.

A System for Storing and Processing the Results of Energy Test Facility Data Monitoring

R. A. Ivanov, N. V. Maksakov*

Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

Abstract — **Substantiation and verification of the energy and economic calculations for solar power plants require initial data and experimental results. The paper proposes a device developed for monitoring and processing information from the experimental solar panel facility. The facility aims to obtain reliable data for the verification of models designed to assess solar resource indices used to justify the performance of solar power plants in the eastern regions of Russia. The device developed for monitoring the energy characteristics of solar panels has additional capabilities to transmit data to the server. A method proposed to transfer data to a server employs a Bluetooth module and a single-board computer Raspberry Pi as an intermediate communication center. The results of the preparatory work for monitoring weather conditions and the Peleng SF-06 pyranometer readings, which employs the developed logger and relies on the proposed method of data transfer to the server are described.**

Index Terms: **Arduino, data logger, pyranometer, solar power, raspberry.**

I. Introduction

Designing and upgrading solar plants require energy and economic calculations to justify them [1–3]. Energy estimates can be obtained by theoretical calculations and experimental observations with subsequent comparison of the collected solar radiation data for their verification.

Experimental data can be obtained in several ways, but they all have drawbacks. Satellite data is expensive and relatively inaccurate because the result of their observations is the difference between the incoming radiation and reflected radiation from the earth's surface. The results of observations from ground-based meteorological stations are given in climate reference books published in the last century. In addition, weather stations, especially those making actinometric measurements, are sparse and if they are far from the area of interest, their data is not always up-to-date [4–5]. Solar radiation can also be estimated using parametric models. These models employ climatic parameters such as temperature, humidity, wind speed, and pressure [6–8].

The main purpose of the study is to verify the results of model calculations performed to assess the solar resource indicators and experimental data obtained using the developed device for storing and subsequently processing the information on the energy performance of solar panels.

II. Description of an Experimental Solar Panel Facility

The solar panel facility at issue is located at the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences in the city of Irkutsk. The test facility consists of three differently oriented solar panels and additional equipment, including hybrid inverters and batteries. A more detailed description of the experimental facility is given in [9].

The primary objectives for the facility are to obtain reliable information to assess the efficiency of solar power plants for various regions, substantiate the optimal inclination angle for the panels and the need to build an automated sun-tracking system. Similar work is carried out by researchers from other institutions too, for example [10].

The inverters installed at the facility have screens that display some instantaneous characteristics, such as voltage and current. Data from inverters can be recorded using additional equipment, which has some drawbacks, including high price and closed software, which does not allow flexible settings and works in the manufacturer's language, most often Chinese [11]. These factors make it necessary to develop a proprietary device for recording and processing the necessary parameters.

* Corresponding author.
E-mail: nikita.max@isem.irk.ru

http://dx.doi.org/10.38028/esr.2022.03.0004
Received September 15, 2022. Revised September 26, 2022.
Accepted October 23, 2022. Available online December 5, 2022.

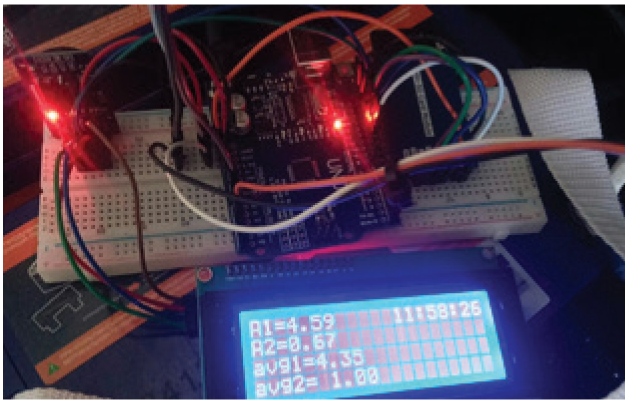


Fig. 1. Data logger based on Arduino microcontroller and shunt ammeter

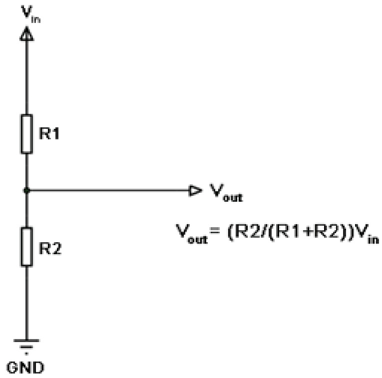


Fig. 2. Voltage divider circuit.

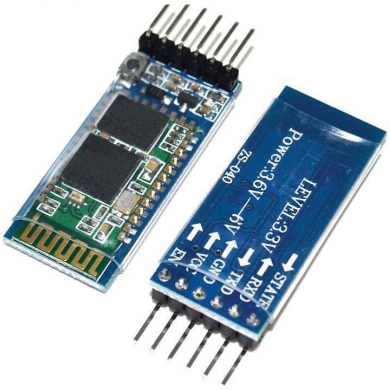


Fig. 3. Bluetooth module HC-06.

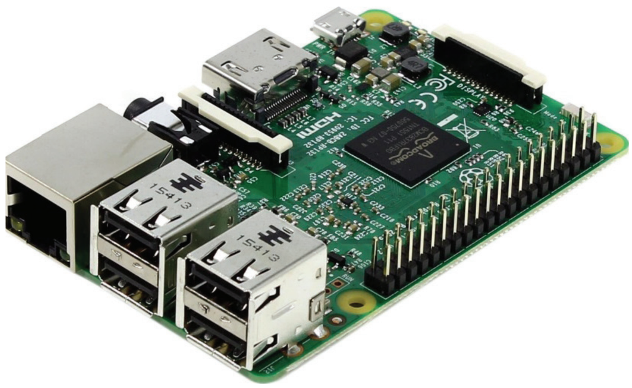


Fig. 4. Single-board computer Raspberry Pi 3.

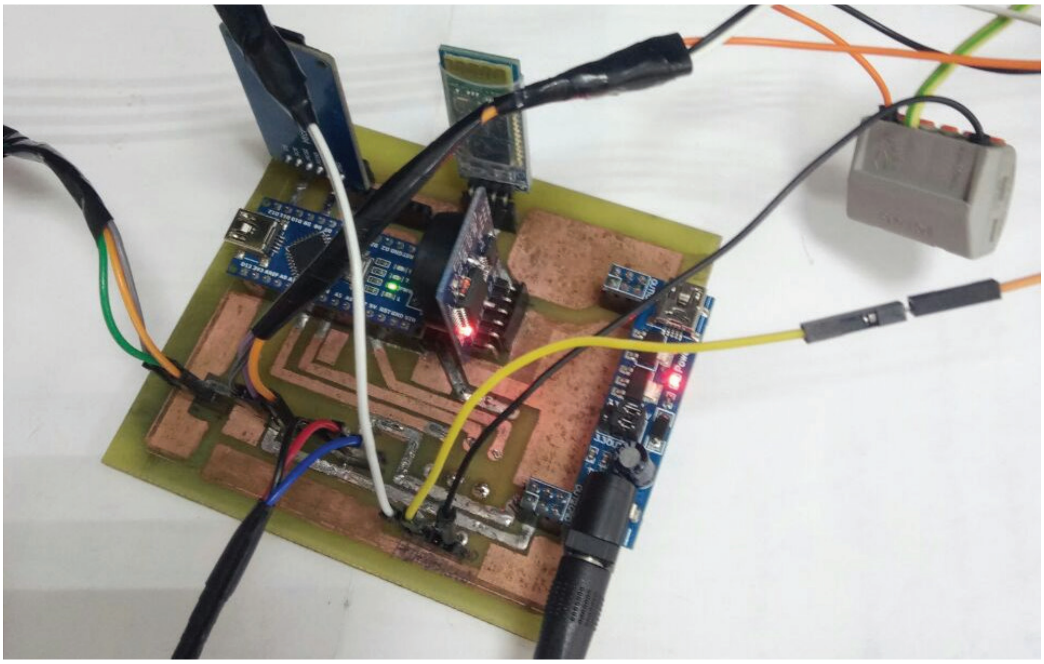
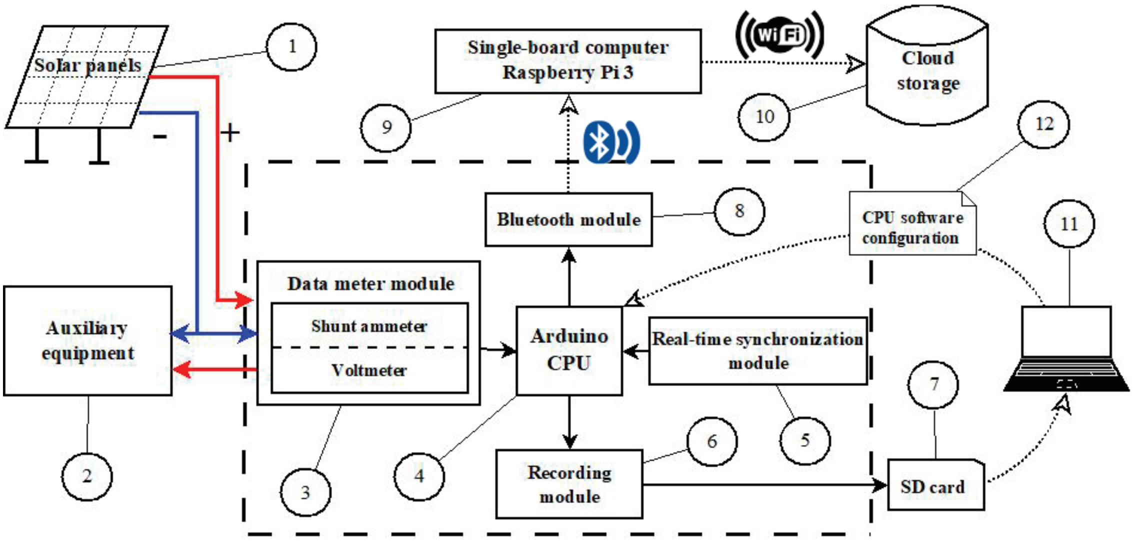


Fig. 5. Customized printed circuit board for the data logger.



— — — the meter circuit; 1 – solar panel; 2 – auxiliary equipment: hybrid inverter and a battery array; 3 – data counter block: shunt ammeter and voltmeter; 4 – Arduino microcontroller; 5 – quartz real-time clock; 6 – device that records data from the meter; 7 – memory card for data storage; 8 – Bluetooth protocol module ; 9 – single-board computer Raspberry Pi 3; 10 – remote server with cloud storage; 11 – computer; 12 – programming instructions for CPU.

Fig. 6. Block diagram of a data logger based on the method of wireless data transmission.

III. Description of the First Version of the Solar Energy Data Logger

The initial stage of the data logger development was aimed at creating a prototype to provide visual monitoring of characteristics.

The Arduino microcontroller was used as a basis, and an ACS712 shunt ammeter based on the Hall effect was used to measure current [12]. An LCD screen was connected to calibrate the sensors.

The next version of the data logger (Fig. 1) was equipped with a real-time module with a built-in lithium battery for independent power supply and acquired the capability to write data to an SD card [9].

This data collection and recoring device is connected to a break in the power circuit and has several modules that are controlled by a microcontroller.

IV. The Current Version of the Solar Energy Data Logger

Previous versions of the data logger were unable to measure voltage. To this end, a voltmeter implemented by a voltage divider (Fig. 2) was chosen for the new version.

With this method, the incoming voltage is reduced from a maximum of 55 V to 5 V and then, the central processor, given the installed resistors, converts the values to those that were before the reduction, with an error of about 0.6 V.

Data is recorded to the server through the Bluetooth module HC-06 (Fig. 3) connected to the data logger and the Raspberry Pi 3 single-board computer (Fig. 4), which runs under a linux-based OS, as an intermediate communication center.

After debugging the sensors, the data logger was assembled on a customized printed circuit board providing modular connection of all components (Fig. 5). The block diagram of this board is shown in Fig. 6.

This board worked in a test mode for several days and showed the good performance of the circuit. Factory-made boards with modular installation of all components were ordered to replace parts that could fail (Fig. 7).

V. Method of Data Transfer to the Server

A bluetooth module is connected to the data logger to transfer data. In our case, this module does not require program code modification. The Raspberry Pi 3 is automatically connected to the data recorder via the Bluetooth protocol and, using a written program in the

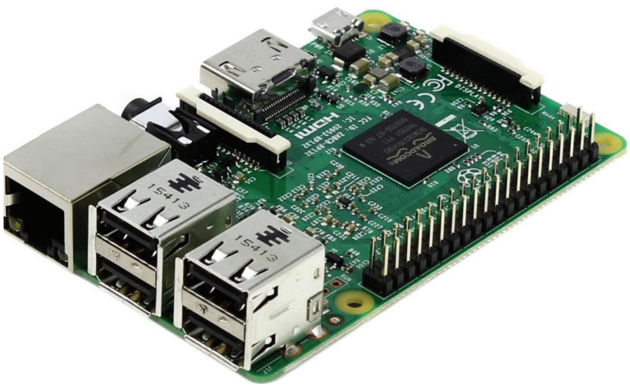


Fig. 7. Data logger assembled on a factory-made printed circuit board.

```
*cloudRec.sh - Mousepad
File Edit Search View Document Help
#!/bin/bash

cd /home/pi/SolarData;
ls |xargs -I{} curl -u Логин:Пароль -T {} https://Адрес сервера/'Данные стенда'/
```

Fig. 8. Terminal command to connect and upload data to the server.

```
File Edit Tabs Help
  GNU nano 3.2              /tmp/crontab.LS6gZe/crontab

#
# For example, you can run a backup of all your user accounts
# at 5 a.m every week with:
# 0 5 * * 1 tar -zcf /var/backups/home.tgz /home/
#
# For more information see the manual pages of crontab(5) and cron(8)
#
# m h  dom mon dow   command
55 23 * * * /bin/bash /home/pi/autosave_solar_panel/cloudRec.sh

^G Get Help  ^O Write Out ^W Where Is  ^K Cut Text  ^J Justify   ^C Cur Pos
^X Exit      ^R Read File ^\ Replace   ^U Uncut Text^T To Spell  ^_ Go To Line
```

Fig. 9. Crontab utility.

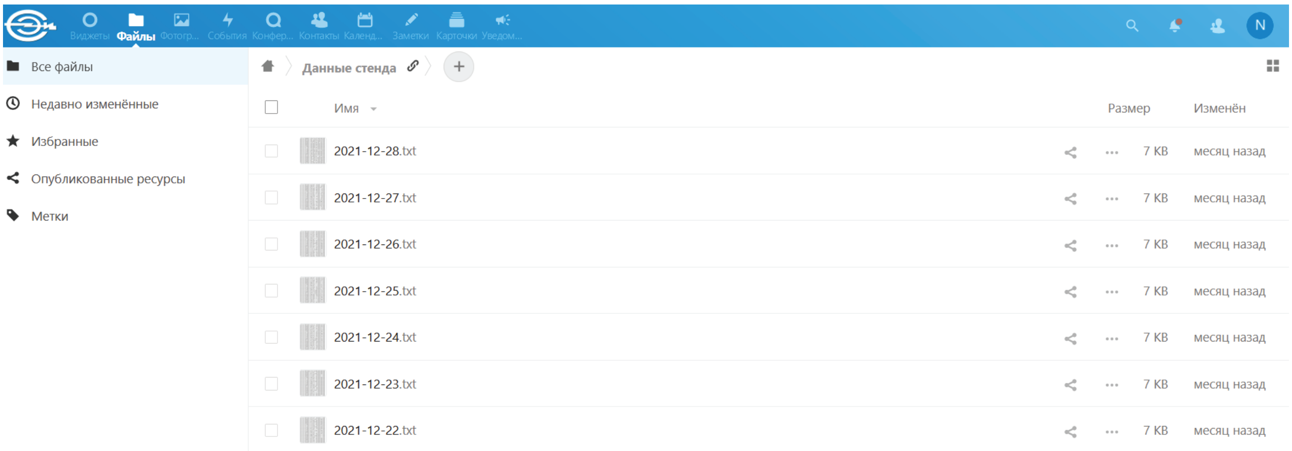


Fig. 10. Data received at the server.

```
https://files.isem.irk.ru/remote.php/v

28.12.21 00:00:01 2.59 0.74 0.07 0.00 0.00 0.00
28.12.21 00:10:01 2.59 1.04 0.07 6.34 6.23 0.00
28.12.21 00:20:01 2.59 0.89 0.37 0.00 0.32 0.00
28.12.21 00:30:01 2.74 0.74 0.44 3.87 3.65 0.00
28.12.21 00:40:01 2.59 0.89 0.52 0.00 0.00 0.00
28.12.21 00:50:01 2.59 0.89 0.59 0.00 0.00 0.00
28.12.21 01:00:01 2.59 0.89 0.15 0.00 0.00 0.00
28.12.21 01:10:01 2.59 0.89 0.30 0.00 0.00 0.00
28.12.21 01:20:01 2.74 0.81 0.15 0.00 0.00 0.00
28.12.21 01:30:01 2.44 0.96 0.30 2.15 2.74 0.00
28.12.21 01:40:01 2.67 0.96 0.44 0.00 0.00 0.00
28.12.21 01:50:01 2.52 0.81 0.37 0.00 0.00 0.00
28.12.21 02:00:01 2.59 0.96 0.07 0.00 0.00 0.00
28.12.21 02:10:01 2.67 0.89 0.37 0.70 0.00 0.00
28.12.21 02:20:01 2.59 0.89 0.52 1.18 0.75 0.00
28.12.21 02:30:01 2.59 1.04 0.15 0.00 0.00 0.00
28.12.21 02:40:01 2.59 0.96 0.37 0.00 0.00 0.00
28.12.21 02:50:01 2.67 1.04 0.44 2.69 3.38 0.00
28.12.21 03:00:01 2.59 0.81 0.15 0.00 0.00 0.00
28.12.21 03:10:01 2.52 0.96 0.30 0.00 0.00 0.00
```

Fig. 11. Open data file.

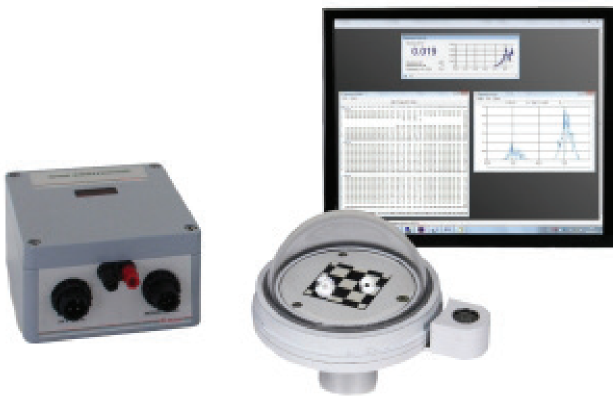


Fig. 12. Pyranometer Peleng SF-06.

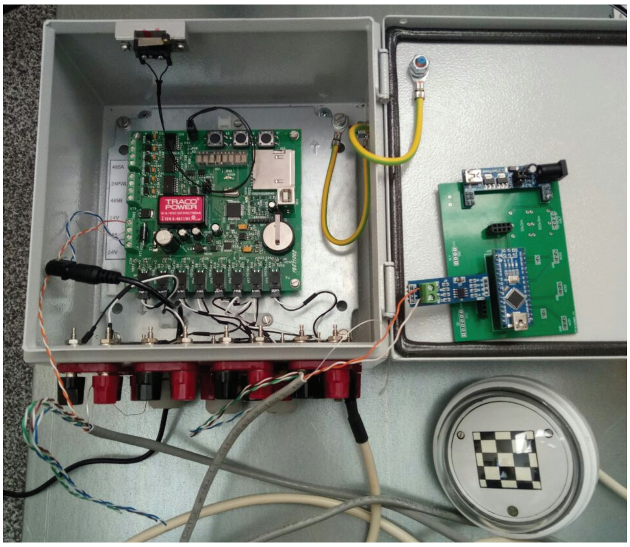


Fig. 13. Pyranometer Peleng SF-06 connected via RS-485.

Python programming language, stores the incoming data in a *.txt file. The created file is named according to the date of data recording. Thus, every day, the data is written to different files for further processing. The generated data is sent to the cloud storage via an Internet connection. In addition, the data is backed up to an SD card to provide backup in case of failure.

To automate the data transfer from the Raspberry Pi 3 to the server, a terminal command was written. It enters the login and password from the account to the server and uploads the data to the desired directory (Fig. 8).

The written command is added to the built-in crontab utility for execution at a specified time (Fig. 9).

The data is stored in a *.txt format convenient for further processing and is available for download. All files are numbered by dates, the file itself keeps a record of the time each line was recorded (Fig. 10 and 11). Data is accessed through a link to the storage.

VI. Logging the Data on Weather Conditions

Theoretical models of solar radiation require data on weather conditions such as temperature, wind speed, pressure, and others. There are ways to develop one's own weather station based on the Arduino microcontroller [13]. These devices use weather sensors and expansion boards to implement the method of data transfer described above. Such devices can be developed directly on the Raspberry Pi 3 with the connection of such sensors [14].

For the objectives of this study, we use the method of data recording from free online weather services of open weather stations. The service is openweathermap.org. This service has a free library for the Python programming language and enables the display of the following data:

- Data update time;
- Temperature (°C);
- Wind speed (m/s);
- Wind direction (°);
- Humidity (%);
- Cloudiness (%);
- Pressure (mm Hg);
- Visibility (m).

To obtain weather data, a program storing the data in a *.txt file was written in the Python programming language. The stored weather data is written to the servers by the same method as the data from solar panels. The terminal program added for automatic execution at specified time on Raspberry Pi 3 connects to the server and uploads files to the specified directory.

It is planned to additionally test the theoretical models using the pyranometer Peleng SF-06 (Fig. 12).

This pyranometer makes it possible to measure the solar irradiance in the spectral wavelength range from 0.3 to 2.4 μm, but does not have convenient tools for data logging. Currently, the proposed solar panel data logger is employed to develop a device for monitoring data from a pyranometer using the RS-485 protocol (Fig. 13).

Since the developed data logger uses the Arduino microcontroller as a central processor, it is possible to correct the firmware and connect other modules to receive the signal.

VII. Conclusion

The new version of the developed device for monitoring the energy performance of solar panels is capable to transmit data to cloud storage for remote access. The paper describes the proposed method for data transfer to a server, which uses a Raspberry Pi 3 single-board computer. It also records the data on weather conditions from open weather stations in real time. The modularity of the developed device makes it possible to replace components in case of a failure or the need to measure another parameter. The SD card allows additional recording of data in the event of the wireless network disconnection. Further data processing will be carried out on a computer and involves the following main steps:

- accumulating data on the total power output for each of the panels;
- visualizing data in the form of graphs, both overall and over a certain period of time;
- comparing data on solar panel instantaneous power.

The work was supported by the grant No. 075-15-2020-787 in the form of a subsidy for a Major scientific project from the Ministry of Science and Higher Education of Russia (project "Fundamentals, methods and technologies for digital monitoring and forecasting of the environmental situation on the Baikal natural territory").

References

[1] O. S. Popel, S. V. Kiseleva, M. O. Morgunova, T. S. Gabderakhmanova, A. B. Tarasenko, "The use of renewable energy sources for energy supply to consumers in the Arctic zone of the Russian Federation," *The Arctic: Ecology and Economy*, vol. 1, no. 17, pp. 64–69, 2015. (In Russian)

[2] I. Yu. Ivanova, T. F. Tuguzova, V. A. Shakirov, N. A. Khalgaeva, “On the need to consider various factors in the justification of the use of solar potential for the purpose of power supply on the example of Yakutia,” *Proceedings of the Russian Academy of Sciences. Power Engineering*, no. 2, pp. 41–54, 2018. (In Russian)

[3] S. E. Frid, N. V. Lisitskaya, O. S. Popel, “Results of the analysis of the applicability of satellite observation data and reanalysis for modeling autonomous solar power plants,” *Doklady Akademii Nauk*, vol. 488, no. 6, pp. 609–611, 2019. (In Russian)

[4] *Reference book on the climate of the USSR.* Issue 22. Irkutsk region and the western part of the Buryat ASSR. Part 1. Solar radiation, radiation balance and sunshine. Leningrad, Russia: Gidrometeoizdat, 1966, 72 p. (In Russian)

[5] *NASA Prediction of Worldwide Energy Resources.* The POWER Project. Available: https://power.larc.nasa.gov/. Accessed on Mar. 12, 2021.

[6] *Scientific and applied reference book on the climate of the USSR. Series 3*. Long-term data. Parts 1–6. Issue 22. Irkutsk region and the western part of the Buryat ASSR. Leningrad, Russia: Gidrometeoizdat, 1991, 609 p. (In Russian)

[7] D. Myers, *Solar Radiation: Practical Modeling for Renewable Energy Applications*. CRC Press/Taylor & Francis Group, 2013, 182 p.

[8] M. J. Ahmad, G. N. Tiwari, “Solar radiation models – A review,” *International Journal of Energy Research*, vol. 35, no. 4, pp. 271–290, 2011. DOI: 10.1002/er.1690.

[9] R. Ivanov, N. Maksakov, “Development of a solar energy meter for an experimental array,” *E3S Web Conf.*, vol. 289, p. 05001, 2021. DOI: 10.1051/e3sconf/202128905001.

[10] S. V. Mitrofanov, A. Yu. Nemaltsev, D. K. Baikasenov, “Primary testing of an automated two-coordinate solar tracker in the climatic conditions of the Orenburg region as a prospect for creating a software and hardware complex,” *International Scientific Journal for Alternative Energy and Ecology*, no. 07–09, pp. 43–54, 2018. (In Russian)

[11] R. A. Ivanov, N. V. Maksakov, “Organization of monitoring the parameters of experimental solar panel facility,” *Information and Mathematical Technologies in Science and Management*, vol. 4, no. 24, pp. 77–87, 2021. DOI: 10.38028/ESI.2021.24.4.008. (In Russian)

[12] *A brief overview of Allegro ACS712 current sensor.* Available: https://www.radiolocman.com/shem/schematics.html?di=113339. Accessed on Feb 04, 2022.

[13] *Analysis of weather station data based on Arduino*. Available: https://habr.com/ru/post/256413/. Accessed on Feb. 04, 2022.

[14] *How to Capture Weather Data with your own IoT Home Station.* Available: https://towardsdatascience.com/how-to-capture-weather-data-on-your-home-400716bde645. Accessed on Feb. 04, 2022.

Current Issues of Russian and Mongolian District Heating Systems and Scientific and Methodological Lines for Solving Them

N.N. Novitsky, Z.I. Shalaginova[1,*], V.V. Tokarev[1], A.A. Alexeev[1],
Tsevegjav Unurmaa[2], Oros Purevjal[3], Jigmed Landannorov[4]

[1] Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia
[2] National Dispatching Center of the Power System of Mongolia
[3] Research Center of Advanced Heat Technology and Techniques, Mongolian University of Science and TechnologyPower Engineering School
[4] MonEnergy Consult LLC

Abstract — **Against the background of the commonality of issues facing district-heating systems (DHSs) in Russia and Mongolia, the prospective strands to overcome them through the widespread adoption of modern methods of mathematical modeling and information technologies are addressed in this paper. A brief description of the long-term experience of cooperation between the Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) and the scientific and energy enterprises of Mongolia in the field of computer technologies for the analysis and development of operating parameters of the DHS is given. The study shows that this experience is in line with the current global trends in the modernization of district heating systems based on their digitalization and smartization. The concept of intelligent (smart) DHSs, their advantages, as well as the issues arising on the way of the DHS transformation into cyber-physical self-controlled systems are revealed. The results of the analysis of the state-of-the-art scientific and methodological developments and software in the field the DHS analysis and control smartization are discussed. The main results obtained at the ESI SB RAS in the formulation of the DHS adaptive control problems and the creation of a single information space are presented along with the methods for resolving specific issues of analysis, identification of models, and DHS optimization. Additionally, the paper focuses on the software developed at the ESI SB RAS to meet new conditions and requirements in three main applications: as a tool for automating calculations when developing adjustment measures to normalize and improve the energy efficiency of operating conditions; as a tool for integrating heterogeneous information resources into a single space; and as a platform for the development and adoption of the DHS computer simulation methods in practice of operational dispatch control.**

Index Terms: **district heating systems, functioning issues, digitalization, smartization, computer modeling.**

I. Introduction

Modern district heating systems (DHSs) in the cities of Russia and Mongolia are unique in scale and complexity of engineering and technical structures of large dimensions. The DHSs in Russia still have no analogues in other countries in terms of their quantity and total capacity [1]. Such systems include heat sources of various types (CHP, boiler houses) operating for common extended and looped heat networks; pumping stations; central and individual heat points with various sets and schemes for connecting local heat consumption systems, and other control units. Many district heating systems are technologically organized according to a hierarchical principle to ensure multi-stage control of heat supply at heat sources, central or individual heat points, directly at heat-consuming installations (in heating, ventilation and hot water systems). They are characterized by multi-loop heat networks; spatial separation; variability in structure, operating parameters, and conditions of operation.

The main line in the development of the Mongolian energy sector is thermal power industry, with 95.7% of electricity generated at thermal power plants [2], which are concentrated in three large cities (Ulaanbaatar, Erdenet, and Darkhan). The largest DHS is located in the country's capital, Ulaanbaatar. In recent years, Ulaanbaatar's DHS has experienced a shortage of thermal energy due to the

* Corresponding author.
E-mail: shalaginova@isem.irk.ru

http://dx.doi.org/10.38028/esr.2022.03.0005
Received October 06, 2022. Revised October 17, 2022.
Accepted October 22, 2022. Available online December 5, 2022.

Table 1. Software for Modeling Heat Networks

No.	Name	Country	Organization
1	ICE “ANGARA-HN”	Russia, Irkutsk	ESI SB RAS
2	ZuluThermo	Saint Petersburg, Russia	Politerm LLC
3	IGS “CityComTeploGraf”	Russia Moscow	“CityCom”
4	GICC “TeploExpert”	Russia, Ivanovo	Teplotex LLC
5	TERMIS	France, Rueil-Malmaison	Schneider Electric
6	NEPLAN Heating/Cooling	Switzerland, Zurich	NEPLAN AG
7	NetSim	Sweden, Stockholm	Vitec Software Group AB
8	STANET	Germany	STANET
9	PSIControl	Germany	PSI SOFTWARE AG
10	Wanda	Netherlands	Deltares
11	PSS Singal	Germany	Siemens

increase in population. This requires an increase in capacity, adjustment of heat consumption systems, automation of individual heat points, and installation of metering units.

The commonality of the district heating problems in Russia and Mongolia is determined by the following main circumstances: 1) severe climatic conditions comparable in terms of daily and annual fluctuations in outdoor temperature and duration of heating period; 2) similar principles of the DHS construction and organization of operation; 3) transition to a market economy and related tightening of requirements for energy efficiency and energy saving.

The common problems also include general aging of the main equipment and poor provision with control, measuring and monitoring equipment. As a result, there is a low degree of DHS controllability, reliability, and efficiency; increased accident rate; high thermal energy losses and energy consumption, and interruptions in energy supply to consumers. On the one hand, work on the adoption of technical means for measuring, automatically recording and regulating thermal energy has been intensified recently. On the other hand, this increases the variability of operating conditions of the district heating systems and significantly complicates the control processes.

The improvement in the reliability, cost-effectiveness, and quality of DHS operation requires a set of measures related to both technical re-equipment of DHS and the adoption of modern information and computing technologies for the analysis and optimization of DHS operation at almost all stages of decision-making: development of heat supply diagrams, design, reconstruction, operation, and dispatch control.

For more than 30 years, the ESI SB RAS has been actively cooperating with scientific and energy enterprises of Mongolia in the field of heat supply [3–5]. Interaction was also organized with the Mongolian University of Science and Technology on the basis of the Department of Thermal Power Engineering to train Mongolian specialists to use software and computing systems for DHS modeling, which were developed at the ESI SB RAS. Since 2014, within the framework of a cooperation agreement with the National Dispatching Center of the Energy System of Mongolia, the two countries have worked to adopt computer technologies for the analysis and development of the operating conditions of district heating system, and concepts for controlling them, given new requirements, equipment, and technologies.

This paper, based on a brief description of the experience of this cooperation and an analysis of the current state and main trends in digitalization and smartization of DHS in other countries, characterizes the most promising areas for the DHS renovation, as well as the scientific and methodological groundwork available at the ESI SB RAS in this area.

II. Experience in Application of Computer Technologies to Provide DHS Operation in Russia and Mongolia

As noted, a significant enhancement in the DHS efficiency becomes impossible without the use of modern information technologies and applied software. This is evidenced by a fairly developed market for foreign and domestic software for computer modeling of district heating systems (Table 1).

The analysis of this market shows [6] that the currently existing software mainly automates typical problems of modeling the DHS operating conditions. At the same time, these software products are as a rule closed in terms of functions, data, and methodological support. These circumstances significantly limit the possibilities of their integration with other information or computing resources, and do not allow developing the information and computing space in the absence of developers, applying mathematical models and methods hidden from the user, and guaranteeing the adequacy and reliability of calculation results. Table 2 presents the results of the analysis of the most common software applied to date for solving non-traditional, but significant problems (analysis and provision of controllability, observability, adaptability, optimal functioning) that arise with the DHS smartization.

TABLE 2. Correspondence of the Existing Software Capabilities to New Requirements

No.	Software	Import-Export	Open data format	Hydraulic calculation	Thermal calculation	Non-stationary conditions	Controllability	Provision of observability	Damageability	Observability	Adaptability	Forecasting	Optimality	Integrability	Analytic functions
1	ICS ANGARA-HN	+/-	+	+	+				+/-				+/-	+	+/-
2	Zulu Thermo	+/-	+/-	+	+									+/-	+/-
3	IGS “CityComTeploGraf”	+/-	+	+	+				+/-					+/-	+/-
4	GCC TeploExpert	+/-		+	+										+/-
5	TERMIS	+	+	+	+	+						+/-	+	+	+
6	NEPLAN Heating/Cooling	+	+	+	+				+/-			+/-	+/-	+	+
7	NetSim	+/-	+/-	+	+								+/-		+/-
8	STANET	+	+/-	+	+								+/-		+/-
9	PSIControl	+	+/-	+	+		+/-				+/-	+/-	+/-	+/-	+/-
10	Wanda	+/-	-	+	+	+							+/-		+/-
11	PSS Singal	+	+	+	+		+/-		+/-		+/-	+/-		+	+/-

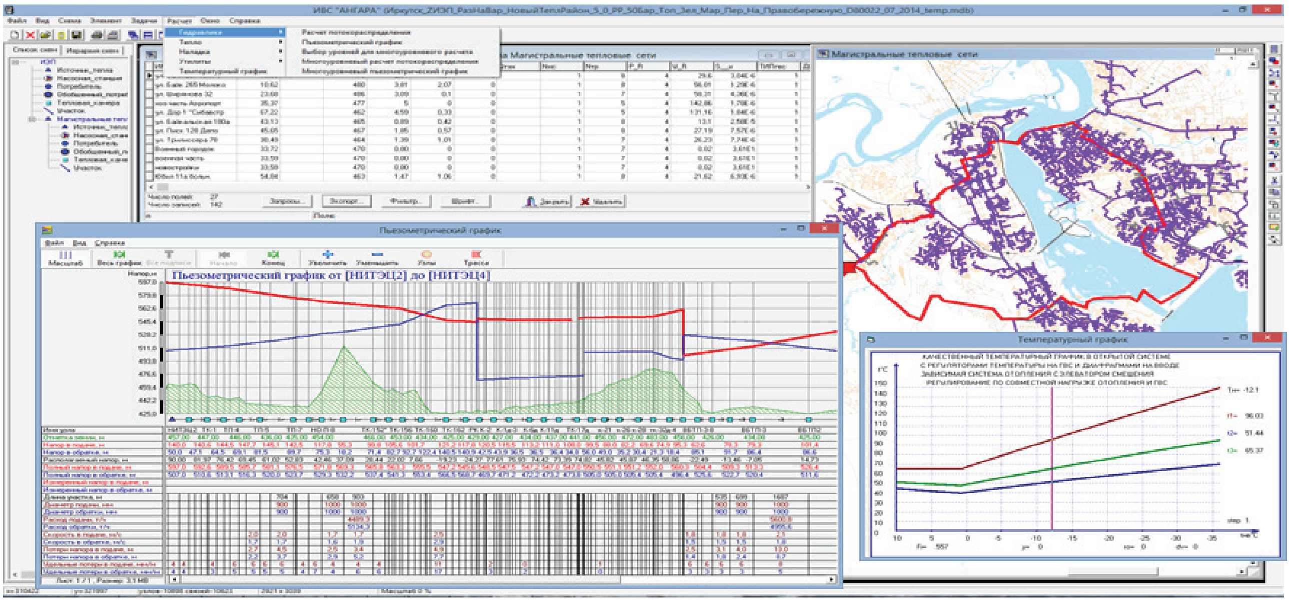


Fig. 1. Interface of the ANGARA-HN software.

Based on the theory of hydraulic circuits, a scientific area developed at the ESI SB RAS, the Institute has accumulated unique experience in creating methodology and software for calculating and optimizing pipeline systems (PLSs) [8].

Since 2000, the proprietary information computing environment (ICE) "ANGARA" has been created and developed here as a universal platform for modeling PLSs of various types and purposes [17, 18]. This ICE automates the processes of setting up the information computing environment of the user, including that without the participation of developers. The use of this environment within a single graphical interface provides many opportunities for PLS computer simulation, information analysis, interpretation of initial data, and calculation results [19].

The most important properties of the ICE areas follows:

- Data are stored in an open form in the format of modern relational DBMS (both local and network ones), there is possibility of expanding the database (DB) structure by the user, organizing interaction with other information systems, and flexibly integrating into a single information space (SIS) of the enterprise;
- Support for multi-level models of pipeline systems is provided to decompose a single design diagram on any basis (territorial, technological, departmental) and harmonize the calculations of individual parts;
- There is a possibility of multi-layer presentation of information according to the network diagrams and terrain plan, including data exchange between layers and computational models, which enables the intersystem interaction between models of different types of pipeline systems during their modeling;
- Support for the processes of end-to-end modeling is ensured, in which once created electronic model can be used in different stages of decision-making: design, reconstruction, operation, dispatch control, training.

The latest version of the ANGARA ICE has a multilingual interface (Russian, English, and Chinese), which can be adapted to any other language.

To automate modeling of the DHS operating conditions, the ESI SB RAS developed the information computing system (ICS) ANGARA-HN [20–22], which is an integration of the ANGARA ICE and the software (Fig. 1). The ICS allows hydraulic and thermal calculation; analysis of feasibility of operating parameters; search for the places of rationally sectioning the heat network; calculation of the parameters of throttling devices to maintain the required operating parameters for the consumer; calculation and construction of temperature and piezometric graphs, and others.

The main distinctions of the ANGARA-HN software are related to its capability to provide the hierarchical single-line or two-line representation of heat network diagrams, their single- or multi-level, detailed or aggregate modeling, and increase in the composition of calculation tasks without reprogramming existing ones on a single information basis. Methods and algorithms for modeling the operating conditions, which are implemented in the ANGARA-HN ICS [23–35] have been extensively tested in the district heating systems of many Russian cities (Moscow, St. Petersburg, Urengoy, Yekaterinburg, Petropavlovsk-Kamchatsky, Irkutsk, Angarsk, Bratsk, Baikalsk, Cheremkhovo, Zheleznogorsk-Ilimsky, etc.) and cities of other countries (Mongolia (Ulaanbaator, Darkhan), Ukraine (Dnepropetrovsk), China (Beijing), and others). This appeared to be possible thanks to long-term close cooperation with many design and operating organizations, research institutes and universities (OJSC Irkutskenergo, OJSC Irkutskteploenergo, grid companies of Irkutsk,

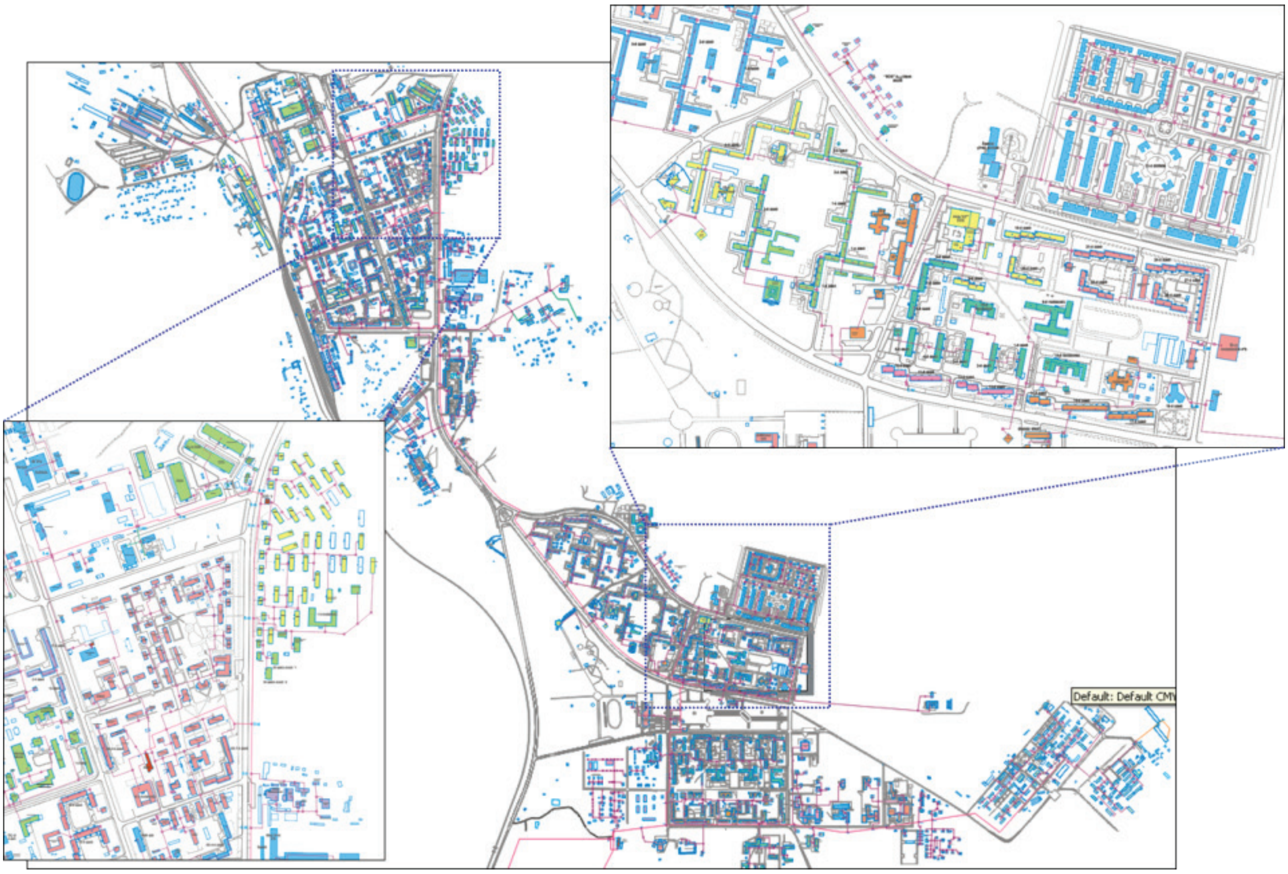


Fig. 2. Heat networks of the city of Darkhan against the backdrop of urban development.

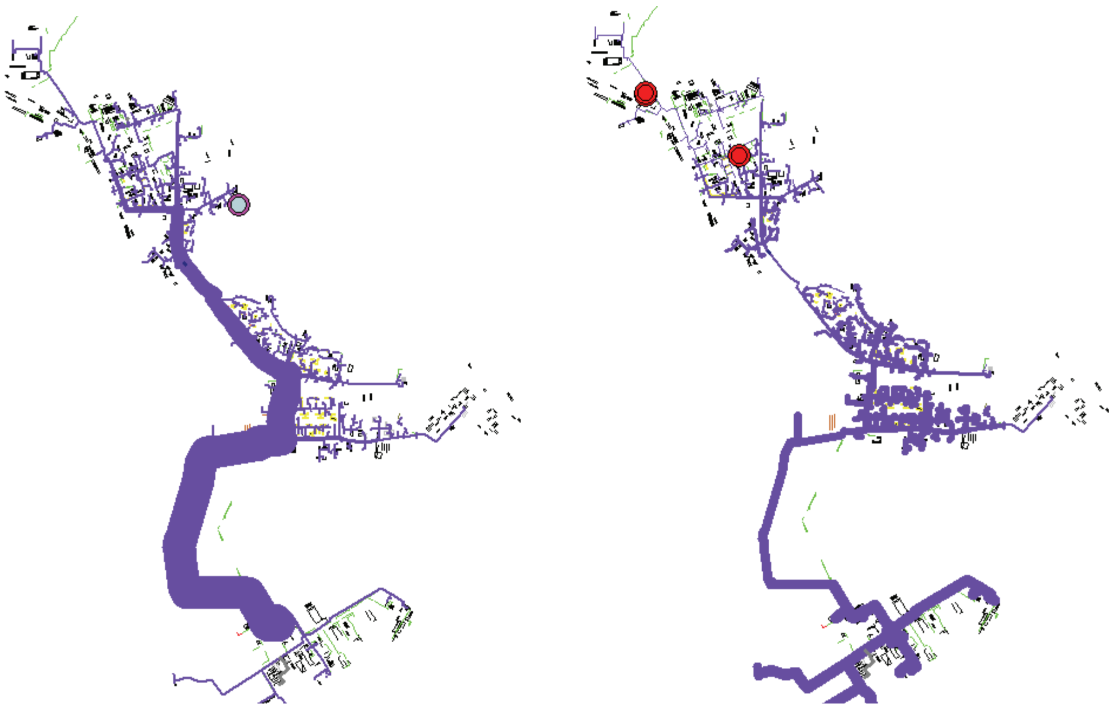


Fig. 3. Analysis of the current state of the heat network in Darkhan, a) distribution of flows (line thickness is proportional to the flow in the supply pipeline), b) distribution of available pressures (line thickness is proportional to the available pressure).

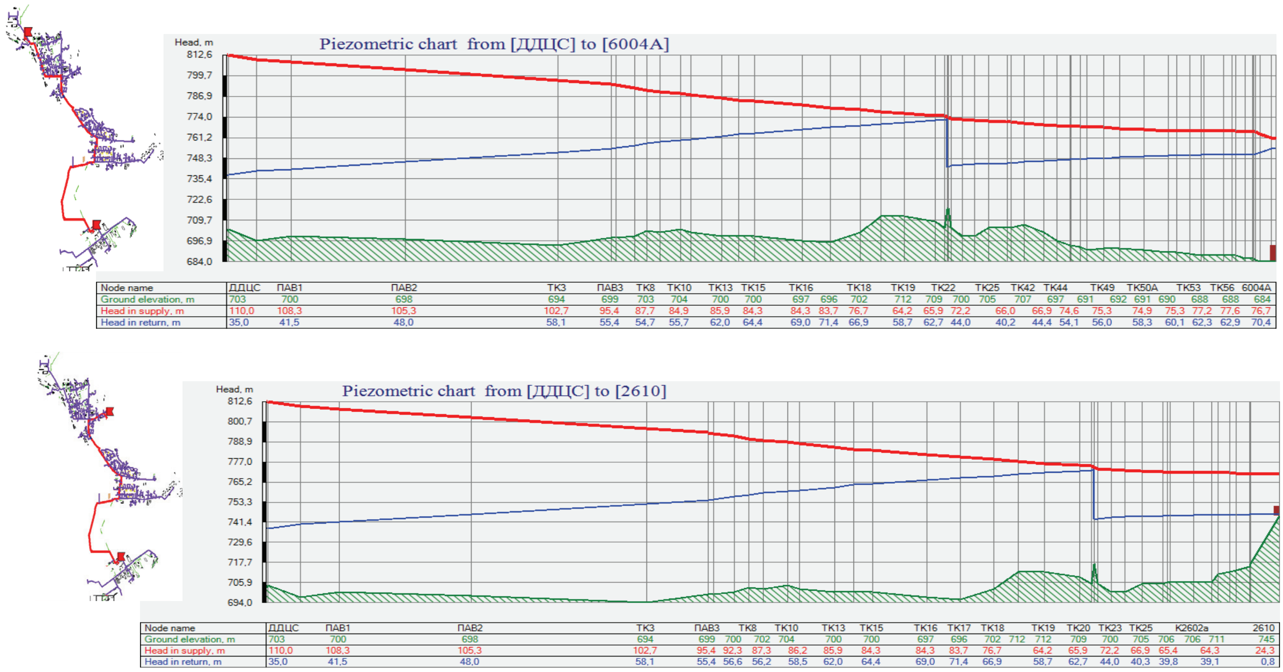


Fig.4. Piezometric graphs of the heat network in the city of Darkhan to the characteristic consumers in terms of available pressure (a) and pressure in return pipeline (b).

OJSC Siberian ENTC (Departments of heat networks and advanced design), Irkutsk State Technical University, PJSC "KamchatskEnergo" (branches "Kamchatskye CHPPs" and "Communal Energy"), OJSC "Gazprom Promgaz," Research Institute of OJSC "VTI," "TEP-Engineering," OJSC "Center of Power Engineers of the Urals," OJSC "DneprVNIPIenergoprom," Urengoy State District Power Plant, National Dispatch Center of Power Systems of Mongolia, Darkhan Heat Network Enterprise, Mongolian University of Science and Technology, and others).

In the vast majority of cases, the use of the software made it possible to identify and, to a large extent, implement a great potential for energy saving, and improve the quality of heat supply to the consumer by reducing the circulating water flow, make-up water flow, water discharges by the residential sector, unproductive heat losses, electricity consumption for pumping and chemical water treatment of coolant, fuel consumption, and others.

The experience of cooperation between the ESI SB RAS and scientific and energy enterprises of Mongolia in the field of heat supply has more than 30 years of history, mainly in the area of the adoption and application of the software developed by the Institute for DHS simulation (modeling). Over this period, several generations of such software have changed. Back in 1992, the interactive computing software "DISIGR," introduced for personal computers running with DOS, was used by Mongolian specialists to calculate the operating conditions of the district heating systems in some cities in Mongolia. In 2000, the software ARMTTS, which combined computational tasks with a graphical database, was handed over to Mongolian colleagues. In 2010, the Windows version of the ANGARA-HN was transferred to and since then it has been maintained at the Department of Thermal Power Engineering of the Mongolian University of Science and Technology, at the National Dispatching Center for Energy Systems of Mongolia, and at the JSC "Darkhan Heat Network." Figure 2 shows an example of fragments of the graphical database of the DHS in Darkhan. The analysis of operating conditions of these heat networks allowed detecting their weaknesses (Figs. 3, 4) and developing adjustment measures.

III. Trends and Strands in Overcoming Existing Issues

In recent decades, the processes of renovation and modernization of district heating systems have been intensified all over the world through the adoption of new equipment and materials; systems for control, monitoring and measurement; computers; remote control systems for collecting and processing the measurements, and methods of mathematical and computer modeling for analysis and decision-making on control. The aim of these transformations is primarily associated with the digitalization and smartization of DHS.

The generalization of the experience of these transformations, as well as the goals and experience of the smartization of electric power systems, made it possible to formulate the concept of smart (intelligent) DHS (IDHS) as a fundamentally new platform, within which it becomes possible to effectively coordinate the interests, requirements, and capabilities of all parties involved in the processes of thermal energy generation, transportation, distribution, and consumption [6, 33, 34]. The consumer is assigned the role of an active equal participant influencing the amount of heat consumed, its quality and prices. The main features of the IDHS are:

1) A single information (digital) space, as the main backbone factor responsible for the observability of the processes of production, distribution, and consumption for all participants in these processes;
2) A high level of controllability as the main way to harmonize the requirements of consumers and the capabilities of producers (suppliers);
3) Dynamic pricing stimulating consumers to change their usual consumption schedules;
4) High proportion of digital, information, and telecommunication technologies; methods of mathematical modeling and optimization in real-world scenarios in the context of monitoring, control, and decision-making.

The main means of implementing the IDHS are not only energy-efficient basic and maneuverable control equipment but also mainly advanced information, telecommunication, and computer technologies. Intelligence is associated with the transfer of the main functions of analysis, forecasting, decision-making, and implementation to software. The greater the number of such functions, which previously required engineering education, experience and qualifications of specialists, are assigned to computer systems, the more "intelligent" DHS is.

The transition to the ISCT platform will require dealing with a whole host of scientific, legal, technical, technological, economic, informational and other issues, including the need to revise the existing practice of design, operation and dispatching control of DHS.

The main issues to be faced can be briefly summarized as follows.

1. *In design*. Traditionally, DHS is designed for one so-called design behavior of maximum load, which follows from the requirement of firm supply to the consumer under any other conditions. However, the system operates in this condition only a small fraction of its total operation time. Under highly uneven consumption (especially with active behavior of the consumer) and low controllability of DHS, this approach leads to an overestimation of investment in development and operating costs. The current design practice does not provide the controllability of the DHS as a whole, and there are no requirements and standards for the controllability of the DHS at all. At best, standard schemes for local automation of individual structures (sources, pumping stations, heating points, etc.) are used. Accordingly, the designed district heating systems are poorly adapted to efficient operation in a variety of possible conditions.
2. *In operation.* The traditional norms for the DHS operation regulate the repair work in accordance with the standard service life of the equipment, i.e., a planned and preventive system is applied. At the same time, with the progressively growing general aging of this equipment, on the one hand, the implementation of these standards becomes unrealistic, and, on the other hand, meeting these standards is not rational. The actual service life of the equipment, depending on the specific conditions of its use, may differ from the normative one by several times, both up and down. The transition to the system of operation according to the actual state, as more efficient, is poorly supported scientifically, methodologically, and normatively.
3. *In control*. The lack of full-scale information-and-measuring systems (IMS) until now has been the main constraint on the development and implementation of advanced concepts of process control, which require the presence of feedback (observability and identifiability of DHS). For this reason, the dominant concept until now has been the simplest concept of control "according to the regulations." According to this concept, control decisions are made on indirect grounds (according to the forecast of outdoor air temperature, return water temperature at sources, etc.) and the consequences of control (the extent to which consumers are provided with heat, feasibility of the conditions, and their optimality) remain partially or completely unobservable, i.e., the feedback principle, as the basis for reliable and sustainable control, is not ensured.

The analysis of these issues allows formulating the following key objectives that arise on the way of the DHS smartization.

1. *In design.* 1) ensure the operational efficiency of the designed and reconstructed DHS, given the use of new concepts and control technologies; 2) develop controllability and observability regulations and standards; 3) synthesize control and information-and-measuring systems.
2. *In operation.* 1) switch to the practice of planning repairs based on the actual state of the equipment; 2) apply methods of active identification, technical diagnostics and damage analysis; 3) optimize plans for repair and restoration work, given the actual state of the equipment, damage statistics and damage to consumers.
3. *In control.* 1) transition to a new concept of controlling district heating systems as dynamic and stochastic objects operating under uncertainty about the internal state and external impacts [33–36]; 2) optimally plan and control the main (operational), post-accident and «repair» conditions; 3) continuously monitor the actual state of the DHS; 4) overcome departmental or corporate disunity of technologically connected parts of the DHS and related systems.

Summarizing what has been said, it is worth stating that the core direction of resolving the traditional contradiction between the requirements for the DHS efficiency and reliability on the way to their smartization involves the enhancement of their controllability based on the mathematical modeling methods. The primary issue that arises here is the need to develop the principles for creating a single digital space, methods and technologies for real-time monitoring of the DHS parameters and states, and the external environment.

IV. Current State of Scientific and Methodological Developments in the Field of Mathematical Modeling of Heat Supply Systems

The analysis of the current state of scientific and methodological developments and software designed to make the processes of DHS control in Russia and other counties [6] intelligent identifies three major classes of tasks: analysis, identification of models, and optimization of operating conditions.

The tasks of analysis (simulation of DHS conditions) arise at almost all stages of decision-making on control, but for different purposes. To design district heating systems, one should analyze the reliability and feasibility of their operation in non-design conditions; during reconstruction, it is necessary to analyze the throughput and identify "bottlenecks" in operation under expected future loads; to plan operation for the upcoming heating season – to develop and justify measures to adjust heat networks; in the case of dispatching control – to analyze and justify control decisions. The models and methods for modeling operating conditions (hydraulic, thermal, stationary, and non-stationary) have been the subject of an extensive literature, a lot of experience has been gained, and the developed methods have become widespread. It is worth noting, however, that this experience is limited in terms of new needs of intelligent DHS, such as the analysis of the cybernetic properties of DHS (controllability, identifiability, efficiency, and others) based on the creation of "digital twins" of DHS for testing new concepts, rules, and algorithms of optimal control. These tasks require considering real conditions of DHS operation: the dynamics of behaviors, the stochastic nature of external disturbances, and the uncertainty about information on the internal state of the equipment. To jointly take into account these factors, further development of methods for mathematical modeling of DHS is necessary. In this regard, the generalized [37] and object-oriented [40] models and methods for calculating the flow distribution, which are developed at the ESI SB RAS, appear to be promising, as they factor in arbitrary equipment (including new one) of DHS and the probabilistic nature of flow distribution [41] affected by stochastic external environment in the case of uncertain information on the actual characteristics of the system components.

The tasks and methods of identifying the DHS vary markedly, which is explained by the variety of goals pursued: 1) identification of equipment characteristics (parametric identification) 2) identification of states (state estimation); 3) damage identification (technical diagnostic tests), and others. In this case, the question inevitably arises whether these goals can be achieved based on available measurements. Therefore, the DHS identification is a complex task that includes two main areas: 1) analysis and synthesis of information-measuring systems (placement/composition, parameters, rate of inquiry of measuring instruments) to ensure the DHS identifiability; 2) development of methods for processing large volumes of measurement information in order to achieve the identification goals set. A review of literature [6] shows that: 1) the synthesis of measurement systems for DHS is still at the initial stage of awareness and development; 2) the parametric identification is mainly reduced to the "calibration" of the DHS electronic models, which involves ensuring the agreement between modeling results and measurements at a limited number of network points, where standard measuring instruments are installed; 3) the first works appear in the field of real-time state estimation of DHS based on the results of measurements, including those coming from heat meters at consumers (steady-state hydraulic and temperature conditions are considered); 4) there is a revival of interest in leak detection based on the joint use of measurements and coolant flow models. Identification of pipeline systems as an independent problem was first formulated [7, 9] and systematically studied [42, 43] in the papers of the ESI SB RAS. In particular, the focus was on the optimal planning of operating conditions, the composition of measurements and processing the results of tests of the pipeline systems for hydraulic and heat losses [40].

The above review of the literature on the tasks and methods for DHS optimization [6] indicates high demand for them at almost all levels of decision-making on control (design, operation, operational control) and, accordingly, a growing number of publications. This testifies to the increasing urgency of the DHS optimization problems, as well as their complexity, the presence of many unsolved problems, and the lack of effective general-purpose methods suitable for wide practical application. This situation is explained by some objective factors: 1) large dimensionality and non-linearity of models of DHS operating conditions; 2) many technological requirements and restrictions; 3) a variety of methods and combinations of control (continuous and discrete), restrictions on the places of their application and magnitude; 4) multi-criteria nature of the majority of emerging problems; 5) the need to take into account the dynamics and stochastics of external conditions, and others. The ESI SB RAS proposed a new hierarchical approach to optimization of the DHS hydraulic conditions and automation of the development of adjustment measures [45]. The main capabilities of this approach and the methods developed within its framework [46, 47] are: 1) their applicability to DHS of almost any dimension; 2) a guarantee of a global solution to be obtained without iterative coordination of solutions at different levels (main and distribution networks); 3) distribution of different optimality criteria (economic, technological, environmental, etc.) and types of control

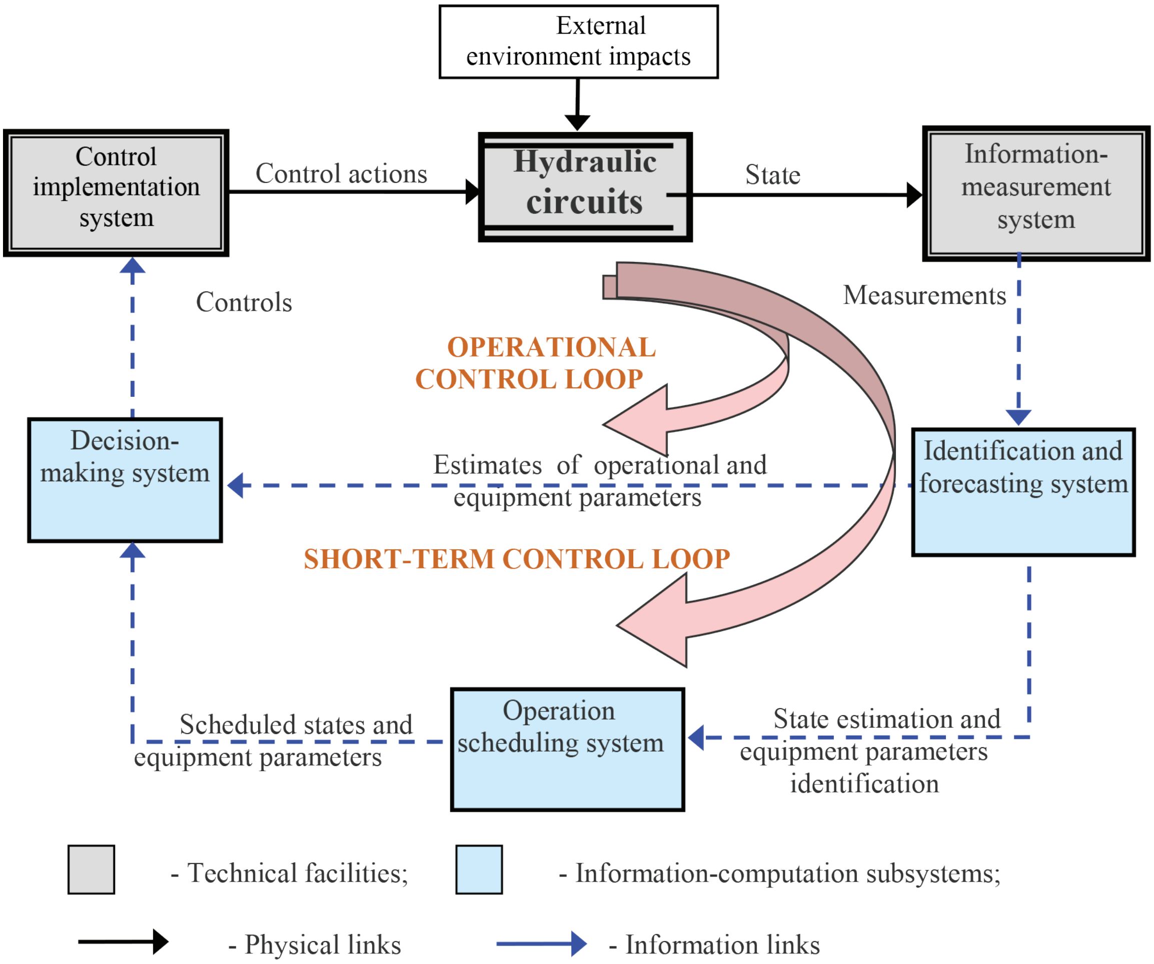


Fig. 5. Loops of causal relationships for controlled DHS.

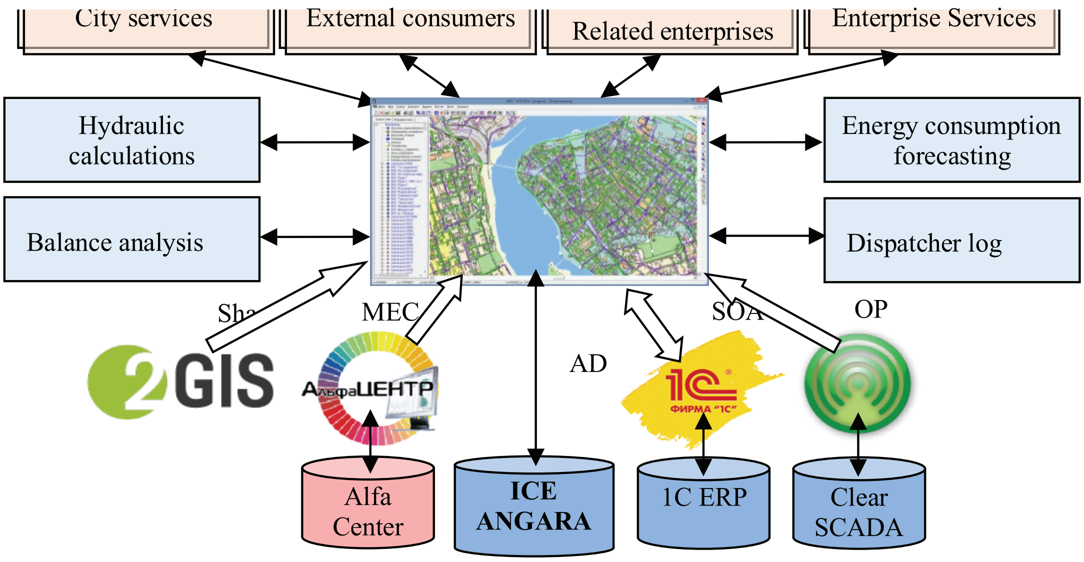


Fig. 6. ICE "ANGARA" as the core of the Single Digital Space of the enterprise.

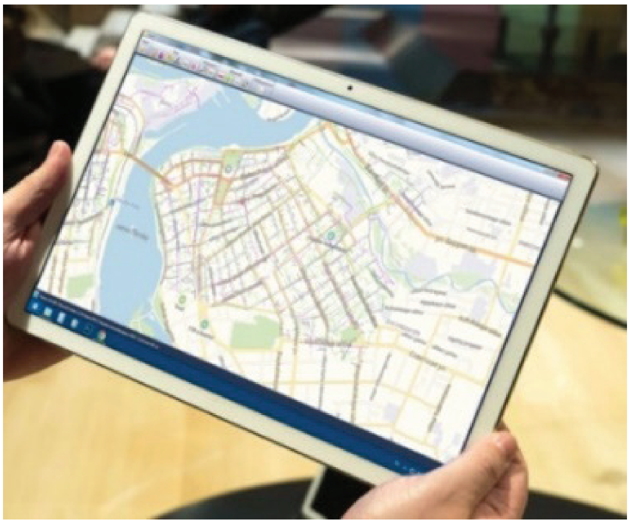


Fig. 7. Graphical interface of the "ANGARA" MIS.

(continuous, discrete, Boolean) according to different levels of the hierarchy; 4) consideration of any technological constraints on operating parameters; 5) consideration of all existing control methods (unit commitment, throttling, frequency control, and others); 5) high performance due to the possibility of conducting parallel calculations.

V. Idea and Technologies of the New DHS Control Concept

An analysis of international experience in the development of district heating technologies shows that at present there are all the necessary prerequisites for the transition to a new advanced concept of compromise adaptive control of DHS operation in the state space with feedback [33, 35–38].

The concept of compromise control means here the need for dynamic coordination of supply and demand between suppliers and consumers, as well as coordination with related systems, through the efficient use of available technical capacities and a flexible tariff policy. Accordingly, in addition to the traditional calendar-time (operation planning, operational control) and territorial-organizational (technological, interdepartmental and intersystem hierarchy) levels of control of operating conditions, it is assumed that there is a level of technical-economic coordination of pricing policy.

The state space is understood as the space of operating parameters (pressures, flow rates, temperatures), the relationship between which satisfies the physical laws of flow distribution, which suggests the use of appropriate mathematical and electronic models. Thus, the DHS control object can be classified as cyber-physical. The qualitative difference between such systems is that they rely not only on the main equipment but also on information and computing resources that directly determine their performance indices.

Adaptive feedback control is understood as the possibility of adapting the models used (through their identification) to changes in the characteristics of the DHS equipment and external impacts based on the monitoring and measurement of the operating parameters and manifestations of the external environment.

Figure 5 shows a stylized flow diagram of the DHS as a cyber-physical system. The main objects of this system are: 1) technical means (the main equipment of the DHS, measurement and control subsystems); 2) information and computing means (for identification of the current DHS state and its projection, optimal operation planning, and operational control).

As seen, this is a full-scale cybernetic system with feedback, and its subsystems are in constant physical, technical, and informational interaction. Different loops of control are associated with the need to factor in its calendar-time nature for decision-making.

The primary problem on the way to the adoption of this concept is associated with a significant increase in the amount of information available for the processes of monitoring and optimal control, and its solution can be found through the creation of a single information (digital) space (SDS) as the basis for coordinating decisions on process control and pricing policy [48]. Such a space, in turn, suggests: 1) integrating the process control and commercial accounting systems into a single information measuring systems (IMS); 2) using new high-speed telecommunication technologies, methods for collecting and processing large amounts of information; 3) providing information to consumers and other participants involved in heat supply processes; 4) creating unified corporate, interdepartmental, territorial (for example, urban) information-measurement systems, which will not only synchronize control decisions but also significantly reduce the cost of these systems themselves.

We developed and tested a technology for creating such a space [49] based on the ANGARA ICE (at the "Vodokanal" company in the city of Irkutsk) (Fig. 6). This technology, in contrast to the known ones, does not involve the establishment of a new information system, but provides integration of existing (or attracted) local information resources (cartography, electronic models, SCADA systems, billing, dispatch logs, etc.) into a single information system. Such a technology provides: 1) completeness, reliability and consistency of information; 2) operational availability of information, both to all interested services and specialists of the enterprise, and to external consumers (city services, related companies, subscribers, etc.) in local or global computer networks; 3) end-to-end support of computational and analytical problems solved at various temporal and territorial levels of control on a single information basis.

In view of the significant scale of the DHS, the problem of the DHS accessibility via wireless communication channels from mobile devices ("smartphone" or "tablet") arises for the enterprise specialists involved in its maintenance at an arbitrary point of the operated facility,

a) a conventional view b) an operational diagram

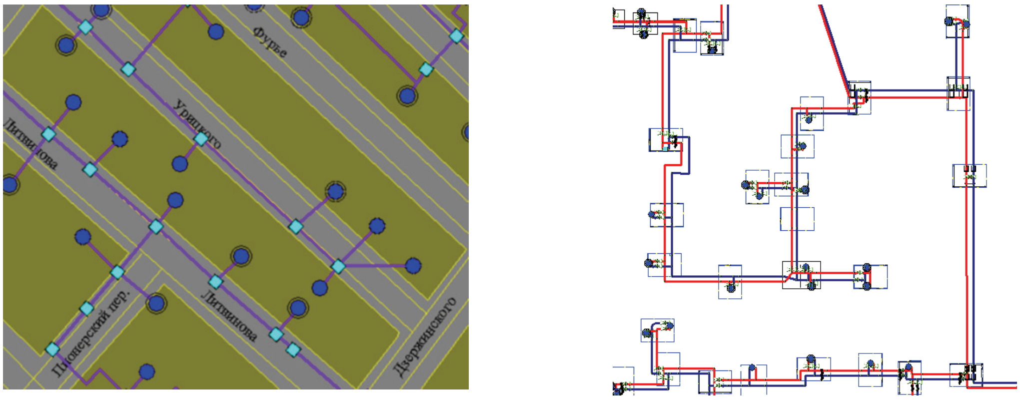


Fig. 8. Representation of the graphic diagram of the heat network in the «ANGARA-DHN» software.

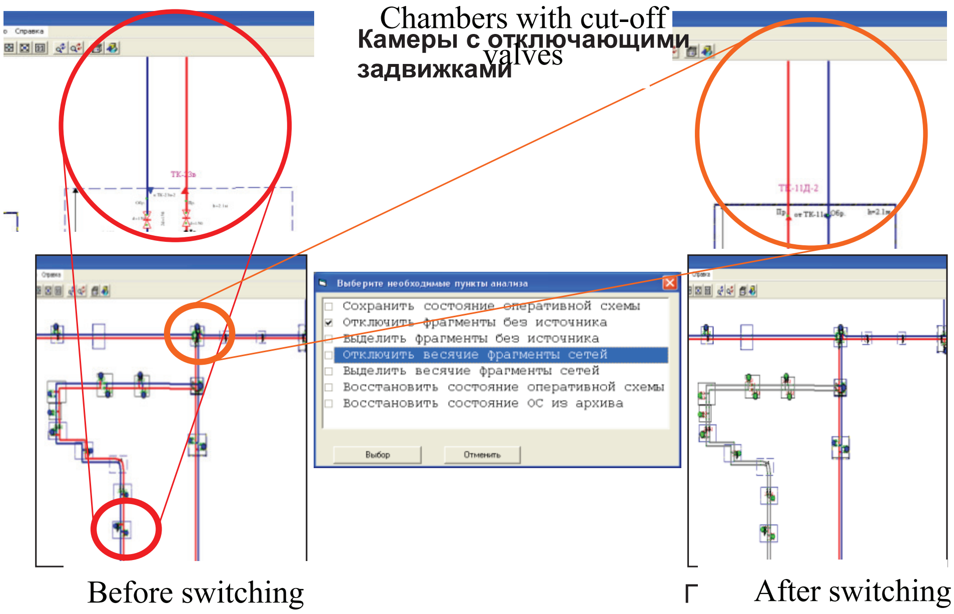


Fig. 9. Search for switches and display of switched off sections on the operational diagram.

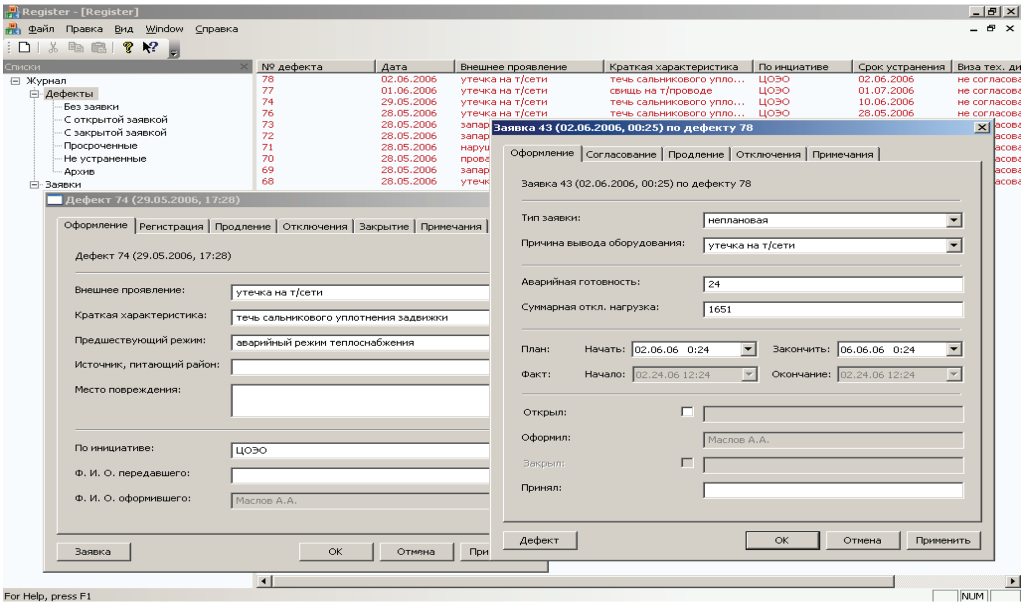
which requires the development of dedicated software. Some works focus on these problems, from the standpoint of the development of both mobile communications [50] and technologies for transmitting large amounts of data on them [51]. To overcome these problems, the ANGARA mobile information system (MIS) was developed, which works on mobile devices under the Windows operating system (Fig. 7). The program is implemented based on .NET Framework and provides users with a basic set of functions: searching, editing, displaying pipeline systems against the background of downloaded satellite maps of the area, logging operations, and automatically synchronizing the data with the SDS of an enterprise.

Solving the problem of information security of the DHS optimal control processes creates the necessary ground for the development and practical application of a whole range of new topical tasks relying on the application of methods of mathematical and computer modeling of the DHS. These are: continuous monitoring and forecasting of consumption and operation parameters; automatic provision of adequacy of electronic models to real-world characteristics of DHS equipment; calculation of optimal parameters for the thermal energy supply from sources; prompt detection of accident sites and development of recommendations for their elimination; optimization and correction of hydraulic and temperature conditions; control of telemetry reliability; maintenance of electronic logs of switching, defects and damages, applications for repair and restoration work, orders and instructions, and many others [52–57].

The ESI SB RAS has developed a pilot version of the ANGARA ICS intended for the use in dispatching control (the ANGARA-DHN software). It allows:

1. displaying heat network diagrams, both in single-line (on the urban development plan) and in two-line representation (operational diagram) (Fig. 8);
2. combining the requirements for compactness and details of the operational diagram (display of primary

a)



b)

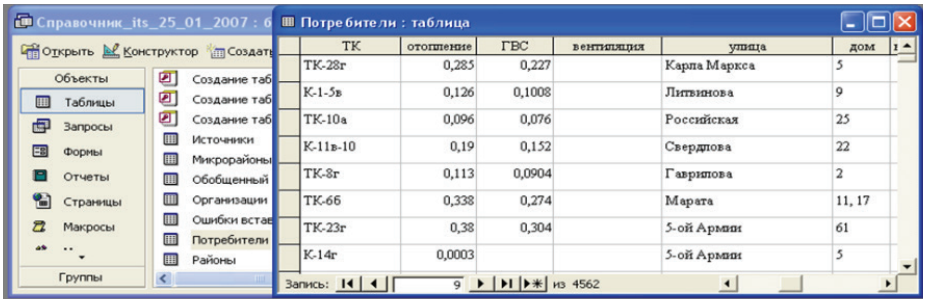


Fig. 10. Interfaces of electronic log of defects and switching points (a) and the reference book on contractual loads (b).

components: pumps, valves, measuring instruments, etc.);

3. supporting multi-level operational diagrams in conjunction with single-line diagrams on the terrain plan;
4. searching for switching points to bring the network component into repair and display disconnected sections on the operational diagram (Fig. 9);
5. conducting operational hydraulic calculations using decomposition, reduction and disaggregation methods, and direct measurement data;
6. assessing the feasibility of operating conditions for the district heating system according to the process conditions of the equipment operation;
7. graphically interpreting “bottlenecks” and places where the requirements for feasibility of operating conditions are not met on diagrams and piezometric graphs;
8. integrating with dispatching electronic logs of defects and switching (Fig. 10), reference books on contractual and current loads of consumers (Fig. 11), and measurement systems.

VI. Conclusion

1. Russia and Mongolia have a long history of fruitful cooperation in building and modernizing DHSs, which has all the grounds for its further development. An analysis of the current energy efficiency and energy saving issues, as well as global trends in the transformation of heat supply technologies, shows that the main way to overcome them lies in the «digitalization» of district heating systems and “smartization” of their control.
2. The main goal of these processes is to build a new generation of DHSs as cyber-physical self-controlled systems, which, not only rely on the main equipment, but are also carriers of information and computing resources that directly affect the DHS efficiency, reliability, and quality. At the same time, the analysis of existing scientific, methodological, and software developments indicates that the scientific and methodological framework, which can be used as the basis for the DHS smartization is currently still in the process of formation, and the existing DHSs are not yet adapted to solving new problems emerging along this way.

3. The paper presents the main results in the field of DHS smartization, which have been obtained at the Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences. In particular, a new concept of adaptive control of the DHS operating conditions, as well as constructive statements and methods for solving new problems of analysis, identification of models, and optimization of DHS operation are proposed. Accordingly, the primary objective of implementing the proposed concept is to provide full-scale feedback with the DHS, as an object of control, in the form of a single information (digital) space.
4. The software developed at the ESI SB RAS is described against the background of a brief review of the most common software products used in Russia and other countries to support electronic DHS models. This software has been widely tested on many real-world DHSs in Russia and Mongolia and continues to evolve with a focus on new conditions and requirements. The considered software includes 1) ICC "ANGARA-HN," as a means to automate calculations for the analysis, development, and justification of adjustment measures to normalize heat supply to the consumer and improve the energy efficiency of operating conditions; 2) a new version of the ICS "ANGARA," as a tool to integrate heterogeneous information resources into a Single Digital Space; 3) ICC "ANGARA-DHN," as a pilot platform to develop the methods of DHS computer simulation and adopt them in the practice of operational dispatch control.

References

[1] I. A. Bashmakov, "Energy efficiency enhancement in heat supply systems. Part 1. Problems of Russian heat supply systems," *Energy saving*, no. 2, pp. 46–51, 2010. (In Russian)

[2] E. G. Gasho, H. Enkhzhargal, L. Batmand, G. Bayarsaikhan, S. Monkhbayar, *Modernization of heat supply systems in Mongolia*. [Online]. Available: https://www.rosteplo.ru/Tech_stat/stat_shablon.php?id=4221/.

[3] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, A. V. Alekseev, "Experience in the development and application of information and computing systems for calculating large heating systems and organizing their operation," in *Proceedings of the International Scientific Conference "Energy and Market Economy,"* Ulaanbaatar, Mongolia, 2005, pp. 323–329.

[4] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, "Current problems of heat supply system control and methodological directions for their solution," in *Proceedings of the International Scientific Conference on Energy Industry Development and Ecology*, Ulaanbaatar, Mongolia, 2010, pp. 145–148.

[5] V. V. Tokarev, N. N. Novitsky, Z. I. Shalaginova, "Calculation technology and experience in using the ANGARA-HN information-computing complex (ICC) in the development of operating behaviors for heat supply systems in large cities," in Proceedings of the Science and Practice Conference on Improvement in planning the district heating system operation, Ulaanbaatar, Mongolia, 2014, pp. 53–64.

[6] N. N. Novitsky, Z. I. Shalaginova, A. V. Alekseev, et al, "Current state, trends and tasks of smartization of heat supply systems (review)," *Thermal Engineering*, no. 5, pp. 65–83, 2022.

[7] A. P. Merenkov, V. Ya. Khasilev, *Theory of hydraulic circuits*. Moscow, Russia: Nauka, 1985, 278 p. (In Russian)

[8] E. V. Sennova, V. G. Sidler, *Mathematical modeling and optimization of expanding heat supply systems*. Novosibirsk, Russia: Nauka, 1985, 222 p. (In Russian)

[9] *Mathematical modeling and optimization of heat, water, oil, and gas systems*, A.P. Merenkov, Ed. Novosibirsk, Russia: Nauka, 1992, 407 p. (In Russian)

[10] E. V. Sennova, M. G. Sukharev, V. K. Averyanov, et al. *Hydraulic circuits. Development of theory and applications*, Novosibirsk, Russia: Nauka, 2000, 273 p. (In Russian)

[11] V. K. Averyanov, A. V. Alekseev, M. I. Alekseev, et al, *Pipeline energy systems: development of mathematical modeling and optimization methods*. Novosibirsk, Russia: Nauka, 2008, 311 p. (In Russian)

[12] A. A. Atavin, N. N. Novitsky, M. G. Sukharev, et al. *Pipeline energy systems: Mathematical and computer technologies for smartization*. Novosibirsk, Russia: Nauka, 2017, 384 p. (In Russian)

[13] *Hierarchical modeling of energy systems*, N. I. Voropay, Ed. Novosibirsk, Russia: Academic Publishing House "Geo," 2020, 314 p. (In Russian)

[14] A. V. Alekseev, O. A. Grebneva, N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, "Mathematical models and methods for assessing and realizing the energy saving potential in the control of heat supply systems," in *Research and Development of the Siberian Branch of the Russian Academy of Sciences in the field of energy efficient technologies*. Novosibirsk, Russia: Research Institute of Molecular Biology and Biophysics, 2009, pp. 38–49. (In Russian)

[15] N. N. Novitsky, A. V. Alekseev, O. A. Grebneva, A. V. Lutsenko, V. V. Tokarev, Z. I. Shalaginova, "Multilevel modeling and optimization of large-scale pipeline systems operation," *Energy*, vol. 184, pp. 151–164, 2019.

[16] Z. I. Shalaginova, V. V. Tokarev, "Development of methods for modeling thermal-hydraulic conditions in time to assess the quality of heat supply system performance," in *Proceedings of XVII All-Russian Scientific Seminar "Mathematical Models and Methods for Analysis and Optimal Synthesis of Developing Pipeline and Hydraulic Systems,"* Irkutsk, Russia, 2020, pp. 63–76. (In Russian)

[17] A. V. Alekseev, N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, "Principles of development and software implementation of the information-computing environment for computer modeling of pipeline and hydraulic systems," in *Methods of Research, Control and Optimization of Pipeline Systems in the Energy Sector: Collected papers*. Novosibirsk, Russia: Nauka, 2007, pp. 221–229. (In Russian)

[18] A. V. Alekseev, N. N. Novitsky, "Computer technology "ANGARA" for the integration of information and computing space in the modeling of pipeline systems," *Scientific Bulletin of NSTU*, no. 2, pp. 26–41, 2017. (In Russian)

[19] N. N. Novitsky, A. V. Alekseev, V. V. Tokarev, "Integrated development and application of information technologies for automating the processes of analysis and development of operating conditions of engineering systems for heat and water supply," *Proceedings of Universities. Investments. Construction. Real Estate*, vol. 8, no. 4, pp. 139–161, 2018. DOI: 10.21285/2227-2917-2018-4-139-161. (In Russian)

[20] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, A. V. Alekseev, O. A. Grebneva, S. Yu. Barinova, "Information and computing complex "ANGARA-HN" for automating the calculation and analysis of operating conditions for the control of large multi-loop heat supply systems," *Proceedings of ISTU*, vol. 22, no. 11 (142), pp. 126–144, 2018. (In Russian)

[21] V. V. Tokarev, A. V. Alekseev, N. N. Novitsky, et al, "Development of the information and computing complex "ANGARA-HN" for automating the development of operating conditions of heat supply systems," in *Mathematical models and methods of analysis and optimal synthesis of developing pipeline and hydraulic systems*. Irkutsk, Russia: ESI SB RAS, 2018, pp. 345–365. (In Russian)

[22] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, A. V. Alekseev, "Principles of implementation and directions of software development for calculating the heat supply systems," in *Information and Mathematical Technologies in Science, Technology and Education. Proceedings of the X Baikal All-Russian Conference*, Irkutsk, Russia, 2005, pp. 285–293. (In Russian)

[23] N. N. Novitsky, Z. I. Shalaginova, V. V. Tokarev, O. A. Grebneva, "Technology for the development of operating conditions of large heat supply systems based on the methods of multilevel thermal-hydraulic modeling," *Proceedings of RAS. Power Engineering*, no. 1, pp. 12–24, 2018. (In Russian)

[24] V. V. Tokarev, Z. I. Shalaginova, "Experience in the application of new technologies for the organization of operating conditions of large heat supply systems," *Proceedings of ISTU*, vol. 59, no. 12, pp. 240–248, 2011. (In Russian)

[25] V. V. Tokarev, Z. I. Shalaginova, "Development of a methodology for multi-level adjustment thermal-hydraulic calculation of heat supply systems and its implementation as part of the ICC "ANGARA-HN"," in *Mathematical models and methods of analysis and optimal synthesis of developing pipeline and hydraulic systems*. Irkutsk, Russia: ESI SB RAS, 2010, pp. 300–314. (In Russian)

[26] Z. I. Shalaginova, V. V. Tokarev, "Applied problems and methodological approaches to planning and implementation of operating conditions in district heating systems," *Thermal Engineering*, vol. 66, no.10, pp. 714–729, 2019.

[27] Z. I. Shalaginova, V. V. Tokarev, O. A. Grebneva, A. V. Lutsenko, "Technologies for mathematical and computer modeling to automate the process of operational states development for heat supply systems," *E3S Web of Conferences*, vol. 209, ID 02026, 2020.

[28] V. V. Tokarev, Z. I. Shalaginova, "Development of operating conditions of district heating systems with quality regulation," *E3S Web of Conferences*, vol. 102, ID 03011, 2019.

[29] V. V. Tokarev, A. V. Alekseev, Z. I. Shalaginova, "Efficiency increasing by development of district heating systems operational modes using graphical analysis," *E3S Web of Conferences*, vol. 102, ID 04003, 2019.

[30] Z. I. Shalaginova, "Estimating the energy saving potential from adjustment works in heat supply systems on the basis of modeling their thermal-hydraulic operating modes," *Thermal Engineering*, vol. 61, no. 11, pp. 829–835, 2014.

[31] Z. I. Shalaginova, "Methods for analyzing operational controllability and their application for estimating the quality of heat supply systems," *Thermal Engineering*, vol. 59, no. 5, pp. 408–413, 2012.

[32] Z. I. Shalaginova, V. V. Tokarev, "Applied problems and methodological approaches to planning and implementation of operating conditions at district heating systems," *Thermal Engineering*, vol. 66, no. 10, pp. 714–729, 2019.

[33] N. N. Novitsky, "Intelligent pipeline systems as a new object of application of the theory of hydraulic circuits," in *Proceedings of the Conference "Energy of Russia in the XXI century. Innovative Development and Management,"* Irkutsk, Russia, 2015, pp. 378–389. (In Russian)

[34] N. N. Novitsky, M. G. Sukharev, et al, "Methodological problems of pipeline system smartization and directions for the development of the theory of hydraulic circuits for solving them," in *Pipeline energy systems: Mathematical and computer technologies of smartization*. Novosibirsk, Russia: Nauka, 2017, pp. 167. (In Russian)

[35] N. N. Novitsky, Z. I. Shalaginova, A. V. Alekseev, et al,

"Smarter Smart District Heating," *Proceedings of the IEEE*, 2020. DOI: 10.1109/JPROC.2020.2990490.

[36] N. N. Novitsky, "Mathematical modeling of hydraulic chains as cyber-physical object," *E3S Web of Conferences*, vol. 216, 2020.

[37] N. N. Novitsky, "Development of methods of the theory of hydraulic circuits for solving problems of heating systems control," *Thermal Engineering*, no. 12, pp. 38–43, 2009.

[38] N. N. Novitsky, "Development of methods of the theory of hydraulic circuits for the analysis and synthesis of the properties of pipeline systems as objects of control," in *Pipeline Systems of Energy: Mathematical Modeling and Optimization*. Novosibirsk, Russia: Nauka, 2010. pp. 58–75. (In Russian)

[39] N. Novitsky, E. Mikhailovsky, "Generalization of Methods for Calculating Steady-State Flow Distribution in Pipeline Networks for Non-Conventional Flow Models," *Mathematics*, vol. 9, no. 8, pp. 796, 2021. DOI: 10.3390/math9080796.

[40] N. N. Novitsky, E. A. Mikhailovsky, "Object-oriented modeling of hydraulic circuits," *Proceedings of ISTU*, no. 7, pp. 170–176, 2012. (In Russian)

[41] N. N. Novitsky, O. V. Vanteeva, "Modeling of flow distribution stochastics in hydraulic circuits," *Proceedings of RAS. Power Engineering*, no. 2, pp. 145–154, 2011. (In Russian)

[42] N. N. Novitsky, *Estimation of the parameters of hydraulic circuits*. Novosibirsk, Russia: Nauka, 1998, 214 p. (In Russian)

[43] N. N. Novitsky, "Elements of the theory and methods of network identification of pipeline systems," *Proceedings of RAS. Power Engineering*, no. 6, pp. 87–97, 2000. (In Russian)

[44] O. A. Grebneva, N. N. Novitsky, "Optimal planning and processing of the results of testing heat networks for hydraulic and heat losses," *Thermal Engineering*, no. 10, pp. 62–67, 2014.

[45] N. N. Novitskiy, A. V. Alekseev, O. A. Grebneva, A. V. Lutsenko, V. V. Tokarev, Z. I. Shalaginova, "Multilevel modeling and optimization of large-scale pipeline systems operation," *Energy*, vol. 184, pp. 151–164, 2019.

[46] N. N. Novitsky, A. V. Lutsenko, "Discrete-continuous optimization of heat network operating conditions in parallel operation of similar pumps at pumping stations," *Global Optimization*, vol. 66, no. 1, pp. 83–94, 2016.

[47] A. V. Lutsenko, N. N. Novitsky, "Optimization of hydraulic conditions of radial district heating systems with pumping stations," *Energy Systems Research*, 2019, vol. 2, no. 1(5), pp. 34–41, 2019.

[48] A. Alekseev, N. Novitsky, "The concept and technology of a unified digital space organizing of an operational enterprise as a necessary condition for the intelligent automation of pipeline systems," *IOP Conference Series: Materials Science and Engineering*, vol. 667, ID 012003, 2019.

[49] A. V. Alekseev, N. N. Novitsky, "Information and computing spaces integration for operating enterprises of pipeline systems using "ANGARA" computer technology," *E3S Web of Conferences*, vol. 39, ID 04001, 2018.

[50] C. Shen, M. Yun, A. Arora, H.-A. Choi, "Efficient Mobile Base Station Placement for First Responders in Public Safety Networks," *Lecture Notes in Networks and Systems*, vol. 70, pp. 634–644, 2020.

[51] R. Siddavaatam, I. Woungang, S. K. Dhurandher, "Efficient Data Transmission Technique for Big Video Files over HetNet in Emerging 5G Networks," *Advances in Intelligent Systems and Computing*, vol. 926, pp. 713–724, 2020.

[52] N. N. Novitsky, V. V. Tokarev, "Modeling of operating conditions of heat networks in tasks of dispatching control," in *Pipeline energy systems: Operation and expansion planning*. Novosibirsk, Russia: Nauka, 2004, pp. 352–361. (In Russian)

[53] Z. I. Shalaginova, "Adaptation of temperature graphs of central control to the operation of heat supply systems based on thermal-hydraulic modeling," in *Pipeline energy systems: Operation and expansion planning*. Novosibirsk, Russia: Nauka, 2004, pp. 372–385. (In Russian)

[54] N. N. Novitsky, A. V. Alekseev, "Methods for calculating feasible hydraulic conditions of pipeline networks," in *Pipeline energy systems: Operation and expansion planning*. Novosibirsk, Russia: Nauka, 2004, pp. 361–372. (In Russian)

[55] N. N. Novitsky, V. V. Tokarev, "Consideration of a variety of flow directions when modeling a steady nonisothermal flow distribution in hydraulic circuits," in *Modern methods of optimization and their applications to energy models*. Novosibirsk, Russia: Nauka, 2003, pp. 178–188. (In Russian)

[56] V. V. Tokarev, N. N. Novitsky, "Investigation of the problems of calculating the actual conditions of heat networks according to measurement data," in *Mathematical models and methods of analysis and optimal synthesis of developing pipeline and hydraulic systems*. St. Petersburg, 2006, pp. 47–50. (In Russian)

[57] N. N. Novitsky, V. V. Tokarev, "Calculation of steady-state thermal-hydraulic operating conditions of heat networks based on a limited number of measurements," *Thermophysics and Aeromechanics*, vol. 14, no. 2, pp. 289–298, 2007.

Nikolay N. Novitsky, Doctor of engineering, chief researcher at the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences (Irkutsk). He is the Chairman of the All-Russian permanent scientific seminar with international participation “Mathematical models and methods for analysis and optimal synthesis of pipeline and hydraulic systems.” His research interests include the theory and methods of analysis, control, optimization and identification of pipeline systems; mathematical and computer modeling. In recent years, he has been actively engaged in theoretical and applied problems of the pipeline systems smartization. He has authored more than 200 published scientific papers.

Zoya I. Shalaginova, Ph.D. in engineering, senior researcher at the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences (Irkutsk). Her research interests include the development and software implementation of methods for modeling the dynamics of thermal-hydraulic conditions of large heat supply systems for the analysis of their controllability. In recent years, she has been actively engaged in the development of methods of multilevel modeling of thermal-hydraulic conditions to analyze the operation of large heat supply systems and develop their operating conditions. She has authored more than 120 published scientific papers.

Vyacheslav V. Tokarev, Ph.D. in engineering, senior researcher at Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences (Irkutsk). His scientific interests include the development of methods of the theory of hydraulic circuits and the use of new information technologies for mathematical modeling of heat supply systems during their operation and dispatching control. He has authored more than 100 published scientific papers.

Alexander V. Alekseev, Ph.D. in engineering, senior researcher at Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences (Irkutsk). His scientific interests include search for feasible and optimal operating conditions of pipeline systems; development and implementation of methods of the theory of hydraulic circuits to solve the problems of dispatching control of pipeline systems; computer modeling. He has authored more than 70 published scientific papers.

Tsevegjav Unurmaa, Ph.D., professor, Head of the Energy Market Department, National Dispatching Center of the Power System of Mongolia, Ulaanbaatar, Mongolia. Her professional activity focuses on the study and application of mathematical models and methods for the calculation and analysis of steady state conditions of Mongolia’s electric power system. She has been actively engaged in the research on the enhancement of the efficiency of the automatic dispatching control system at all territorial and temporal levels of Mongolia’s electric power system control; on the increase of the reliability, efficiency of operation, and power quality; on the improvement of the performance of specialists of the National Dispatching Center of Mongolia.

Oros Purevjal, Consulting engineer, Research Center of Advanced Heat Technology and Techniques, Mongolian University of Science and Technology Power Engineering School, Ulaanbaatar, Mongolia. His professional interests include the application of methods for calculating variable conditions in heat supply systems, the adoption of technologies to enable heat supply systems to quantitatively regulate heat supply under variable heat consumption, and the development of hydraulic conditions of a heat network. He was involved in more than 80 studies and projects for the development of the energy policy, the improvement of technologies for the heat supply systems, and modernization of engineering technologies. The projects have been put into production. He has 6 monographs and 54 publications in international and national editions, of which 10 are concerned with the efficient technologies. He has made more than 30 reports at scientific conferences.

Jigmed Landannorov, M.S. in engineering, Consulting Engineer of the Technical Consulting Service Department. MonEnergy Consult LLC, Ulaanbaatar, Mongolia. The area of his activity is the development of heat supply in the cities and population centers of Mongolia. In recent years, he has worked on the improvement in operating conditions of the heat supply systems in provincial centers and the development of a heat supply system for a newly designed city with a population of 150 thousand people in the area of the new Chinggis Khaan International Airport in the province of Dzunmod.

Relationship Between Energy Consumption and Industrial Structure

Liu Xueyao*

Belarusian State University. 31 Karl Marx St., Minsk, Belarus.

***Abstract* — This paper analyses the differences in energy consumption by industry and studies the relationship between industrial structure and energy consumption in China. The findings of the study indicate that energy consumption is mostly concentrated in the sector Industry. Energy consumption for most Chinese provinces is greatly affected by the share of tertiary industry. In some provinces, however, the energy consumption tends to be influenced by the share of secondary industry. Depending on the specific situation, appropriate recommendations are proposed to each province.**

***Index Terms*: Energy consumption; industrial structure; energy structure; grey relational analysis; energy sustainability.**

I. Introduction

The aim of sustainable development makes the optimization and upgrading of industrial structure the main means of national macroeconomic regulation and control. The adjustment of industrial structure will effectively accelerate economic development and stimulate potential. However, since energy consumption differs among industries, the adjustment of industrial structure inevitably influences regional energy consumption. Scholars in China and other countries discuss the relationship between energy consumption and industrial structure. According to the studies, industrial restructuring has a significant effect on energy consumption. The influence of industrial structure on energy consumption varies among regions because of the disparities in the economic development and the resource endowment. However, there is still a lack of research on the specific impact of industrial structure on regional energy consumption in China. This study examines the differences in energy consumption among industries and the effect of industrial structure on energy consumption in China based on the recent data. The paper provides reasonable and effective suggestions to achieve sustainable economic growth in each region in China.

II. Inter-Industry Differences in Energy Consumption

The economic development in China is currently in the late stage of industrialization, where the heavy industry dominates. The sector Industry has a great demand for energy. According to the statistics of 2019, the sector Industry accounts for 66.16% of the total energy consumption, while the other sectors have significantly lower proportions: Agriculture, Forestry, Animal Husbandry and Fishery (1.85%), Construction (1.88%), Transport, Storage and Post (9.01%), Wholesale and Retail Trades, Hotels and Catering Services (2.79%), Residential (12.66%), and Others (5.66%).

In addition, in the sector Industry, some industries are characterized by unbalanced energy consumption. These are Smelting and Pressing of Ferrous Metals (13.41%), Manufacture of Raw Chemical Materials and Chemical Products (10.93%), Processing of Petroleum, Manufacture of Non-metallic Mineral Products (6.84%), Coal and Other Fuels (6.68%), and Production and Supply of Electric Power and Heat Power (6.51%). These industries belong to the category of heavy industry of China with high demand for energy and capital.

The data in Tables 1 and 2 indicate that major consumer of primary energy sources such as coal (96.36%), crude oil (99.99%), natural gas (68.37%) and electricity (67.72%) is also the sector Industry. Within the sector Industry, coal and crude oil are mainly consumed by the industries related to mining, processing and conversion of energy. While natural gas and electricity are used in part for energy conversion and basic supply, the rest of the energy demand is concentrated in the manufacture of metals or minerals and the manufacture of chemical raw materials and chemical products. These industries belong to the category

* Corresponding author.
E-mail: 18215686524@163.com

http://dx.doi.org/10.38028/esr.2022.03.0006
Received October 11, 2022. Revised October 19, 2022.
Accepted October 27, 2022. Available online December 5, 2022.

Table 1. Energy Consumption by Sector

Sector	Coal	Coke	Crude Oil	Gasoline	Kerosene	Diesel Oil	Fuel Oil	Natural Gas	Electricity
Agriculture, Forestry, Animal Husbandry and Fishery	0.55%	0.13%		1.86%	0.28%	9.89%	0.03%	0.04%	1.78%
Industry	96.36%	99.77%	99.99%	1.92%	0.28%	8.65%	55.70%	68.37%	67.72%
Construction	0.16%	0.02%		3.67%	0.41%	3.55%	0.68%	0.09%	1.32%
Transport, Storage and Post	0.07%		0.01%	45.82%	93.39%	66.14%	43.18%	11.16%	2.34%
Wholesale and Retail Trades, Hotels and Catering Services	0.59%	0.04%		2.11%	0.39%	1.37%	0.22%	2.04%	4.26%
Others	0.65%	0.01%		16.44%	4.66%	6.40%	0.20%	1.87%	8.37%
Residential	1.63%	0.03%		28.17%	0.59%	4.00%		16.42%	14.21%

of heavy industry and have a great demand for resources and capital.

The main coal consumer within the sector Industry is Production and Supply of Electric Power and Heat Power (50.21%), which accounts for more than half of the total coal consumption in the sector Industry. It is followed by Processing of Petroleum, Coal and Other Fuels (13.43%), Smelting and Pressing of Ferrous Metals (6.96%), Manufacture of Non-metallic Mineral Products (5.63%), Mining Products (5.63%), Mining and Washing of Coal (5.51%), Manufacture of Raw Chemical Materials and Chemical Products (5.48%), Smelting and Pressing of Non-metallic Mineral Products (5.63%), Smelting and Pressing of Non-ferrous metals (5.17%). They all account for a relatively large share of coal consumption. Similarly, almost all of China's crude oil consumption comes from the sector Industry. Within the sector Industry, Processing of Petroleum, Coal and Other Fuels consumes 93.99% of crude oil consumed in the entire sector. It is evident that most of the crude oil is used for conversion to other types of fuels. In addition, the sector Industry accounts for 68.37% of the total natural gas consumption, with the Manufacture of Raw Chemical Materials and Chemical Products (13.39% of total sectoral consumption), Production and Supply of Electric Power and Heat Power (16.11%), Extraction of Petroleum and Natural Gas (5.06%), Processing of Petroleum, Coal and Other Fuels (5.61%), and Manufacture of Non-metallic Mineral Products (5.83%) consuming a large proportion of natural gas within the sector. From the perspective of electricity consumption within the sector Industry, it is significantly higher in Production and Supply of Electric Power and Heat Power (12.07%), Smelting and Pressing of Non-ferrous Metals (8.91%), Smelting and Pressing of Ferrous Metals (8.63%), Manufacture of Raw Chemical Materials and Chemical Products (7.25%), Manufacture of Non-metallic Mineral Products (5.02%), whereas in the other industries, it is relatively balanced.

As for the other energy sources, energy consumption structures are sector- and industry-specific. Energy demand in the sector Industry is mostly concentrated in the heavy industries, except for the condition where the sector Industry does not have a significant demand for a certain energy. The heavy industries absorb large amounts of resources and capital and are generally the pillar. However, these industries tend to have problems such as energy waste and excessive pollution. And due to various factors like industrial structure, it is difficult for these industries to transform their existing production patterns to reduce their energy input and pollution output.

The sector Industry consumes almost all energy coke available with the share of 99.77% of the total coke consumption. Most of the coke consumption within the sector Industry (84.54%) falls on the Smelting and Pressing of Ferrous Metals, which also belongs to the heavy industry category. However, gasoline consumption in the sector Industry only accounts for 1.92% of the total consumption, which is much lower compared to the consumption in all other sectors. The sector Industry shows relatively balanced consumption of gasoline for various industries with a quite low share of total gasoline consumption in the sector. Moreover, there is not any significant difference in gasoline consumption between the industries. Kerosene consumption in the sector Industry accounts for only 0.28% of its total consumption. The sector Transport, Storage and Post is the largest kerosene consumer, which accounts for 93.39%. Similarly, due to the low total consumption of kerosene in the sector Industry, it is clear that there is no significant demand for this resource, thus, the kerosene consumption is relatively balanced within the sector Industry and there is no significant difference in its consumption between the industries. The consumption of diesel oil by the sector Industry is also insignificant, with 8.65% of the total diesel oil consumption, which is significantly lower than 66.14% of diesel oil consumption in the sector Transport, Storage and Post. In the sector Industry, diesel oil is mainly used in the Manufacture of Non-metallic Mineral Products (2.11%), Mining and Washing of Coal (1.02%), and Professional and Support Activities for Mining (1.03%), which also belong to the heavy industry category having a great demand for resources and capital. Fuel oil consumption is concentrated in the sector Industry (55.70%) and in the sector Transport, Storage and Post (43.18%). Within the sector Industry, there are significant inter-industry differences in fuel oil consumption, with 40.40% of fuel oil consumed in Processing of Petroleum, Coal and Other Fuels and 11.99% in Manufacture of Raw Chemical Materials and Chemical Products. The demand for fuel oil in the other industries is significantly lower.

Table 2. Energy Consumption by Industry part 1

Industry	Coal	Coke	Crude Oil	Gasoline	Kerosene	Diesel Oil	Fuel Oil	Natural Gas	Electricity
Coal Mining and Washing	5.72%	0.11%		1.89%	6.84%	11.83%	0.01%	8.92%	2.03%
Petroleum and Natural Gas Extraction	0.03%		0.95%	2.67%		3.15%	0.23%	1.18%	0.86%
Mining and Processing of Ferrous Metal Ores	0.05%	0.32%		0.31%		3.30%		7.41%	0.83%
Mining and Processing of Non-Ferrous Metal Ores	0.02%	0.01%		0.63%	4.19%	1.69%	0.04%		0.76%
Mining and Processing of Nonmetal Ores	0.19%	0.02%		0.40%	0.18%	4.17%		0.03%	0.51%
Professional and Support Activities for Mining	0.15%			1.46%		11.92%	0.02%	0.08%	0.08%
Mining of Other Ores						0.01%		0.22%	0.42%
Processing of Food from Agricultural Products	0.44%	0.27%		2.71%	0.82%	1.67%	0.06%	67.14%	1.57%
Manufacture of Foods	0.42%			1.61%		0.64%	0.04%	1.51%	0.60%
Manufacture of Liquor, Beverages and Refined Tea	0.16%			1.10%	0.55%	0.37%	0.01%	1.16%	0.34%
Manufacture of Tobacco				0.15%		0.08%		0.80%	0.10%
Manufacture of Textile	0.20%	0.01%		2.13%	0.27%	0.46%	0.13%	0.06%	3.47%
Manufacture of Textile, Wearing Apparel and Accessories	0.01%			1.87%	0.46%	0.42%	0.02%	2.15%	0.46%
Manufacture of Leather, Fur, Feather and Related Products and Footwear	0.01%			1.09%	0.09%	0.15%	0.01%	0.52%	0.31%
Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	0.02%			0.65%		0.40%	0.01%	0.10%	0.55%
Manufacture of Furniture				0.92%		0.23%	0.01%	0.14%	0.23%
Manufacture of Paper and Paper Products	1.02%			0.96%	0.09%	1.20%	0.31%	0.08%	1.47%
Printing and Reproduction of Recording Media	0.02%			1.37%	0.09%	0.33%	0.02%	1.08%	0.26%
Manufacture of Articles for Culture, Education, Arts and Crafts, Sport and Entertainment Activities				1.26%	1.00%	0.27%	0.02%	0.24%	0.18%
Processing of Petroleum, Coal and Other Fuels	13.94%	0.15%	94.00%	10.64%	1.64%	8.35%	72.54%	0.67%	2.36%
Manufacture of Raw Chemical Materials and Chemical Products	5.68%	8.67%	5.05%	5.40%	17.32%	3.05%	21.53%	8.20%	10.71%
Manufacture of Medicines	0.20%	0.01%		1.50%	0.09%	0.45%	0.10%	19.58%	0.80%
Manufacture of Chemical Fibers	0.34%	0.04%		0.23%	0.18%	0.13%	0.02%	0.72%	0.90%
Manufacture of Rubber and Plastics Products	0.10%			3.61%	0.55%	0.92%	0.13%	0.68%	2.81%
Manufacture of Non-metallic Mineral Products	5.84%	2.89%		5.63%	7.57%	24.35%	3.69%	0.85%	7.42%
Smelting and Pressing of Ferrous Metals	7.23%	84.73%		1.28%	0.18%	4.10%	0.02%	8.53%	12.74%
Smelting and Pressing of Non-ferrous Metals	5.36%	0.88%		1.29%	4.92%	2.62%	0.53%	6.58%	13.16%
Manufacture of Metal Products	0.09%	1.01%		4.43%	4.10%	1.51%	0.06%	2.69%	3.30%
Manufacture of General Purpose Machinery	0.01%	0.53%		5.84%	14.77%	1.65%	0.03%	3.02%	1.99%
Manufacture of Special Purpose Machinery	0.01%	0.02%		4.52%	7.02%	1.12%	0.02%	1.04%	0.99%
Manufacture of Automobiles	0.03%	0.03%		9.44%	2.46%	2.09%	0.01%	0.99%	2.03%
Manufacture of Railway, Ship, Aerospace and Other Transport Equipment	0.01%			1.34%	8.66%	0.87%	0.05%	1.28%	0.33%
Manufacture of Electrical Machinery and Apparatus	0.01%			5.70%	3.83%	0.83%	0.08%	1.05%	1.69%
Manufacture of Computers, Communication, and Other Electronic Equipment	0.11%			3.66%	1.37%	0.50%	0.02%	0.57%	2.96%
Manufacture of Measuring Instruments and Machinery				1.47%	1.09%	0.08%		1.64%	0.15%

Table 2. Energy Consumption by Industry part 2

Industry	Coal	Coke	Crude Oil	Gasoline	Kerosene	Diesel Oil	Fuel Oil	Natural Gas	Electricity
Other types of Manufacture				0.26%	0.73%	0.09%		0.05%	1.14%
Utilization of Waste Resources	0.03%	0.21%		0.12%	0.18%	0.38%	0.05%	0.21%	0.11%
Repair Service of Metal Products, Machinery and Equipment				0.17%	8.48%	0.34%	0.01%	0.92%	0.03%
Electric Power and Heat Power Production and Supply	52.11%	0.09%		8.23%		4.04%	0.15%	23.95%	17.82%
Gas Production and Supply	0.44%			0.97%		0.11%		23.56%	0.37%
Water Production and Supply	0.01%			1.13%		0.15%		0.36%	1.17%

Table 3. Impact Coefficients by Industry in Each Province in China

Region	Primary Industry	Secondary Industry	Tertiary Industry	Industry with the greatest impact on energy consumption
CHINA	**0.587**	**0.566**	**0.814**	**Tertiary Industry**
Anhui	0.548	0.649	0.776	Tertiary Industry
Beijing	0.542	0.768	0.954	Tertiary Industry
Chongqing	0.469	0.485	0.887	Tertiary Industry
Fujian	0.495	0.717	0.869	Tertiary Industry
Gansu	0.436	0.650	0.835	Tertiary Industry
Guangdong	0.462	0.618	0.919	Tertiary Industry
Guangxi	0.817	0.598	0.821	Tertiary Industry
Guizhou	0.618	0.662	0.874	Tertiary Industry
Hainan	0.497	0.619	0.787	Tertiary Industry
Hebei	0.585	0.700	0.752	Tertiary Industry
Henan	0.479	0.709	0.689	Secondary Industry
Heilongjiang	0.716	0.626	0.789	Tertiary Industry
Hubei	0.517	0.709	0.882	Tertiary Industry
Hunan	0.457	0.677	0.847	Tertiary Industry
Jilin	0.458	0.589	0.647	Tertiary Industry
Jiangsu	0.505	0.845	0.952	Tertiary Industry
Jiangxi	0.494	0.631	0.902	Tertiary Industry
Liaoning	0.638	0.692	0.696	Tertiary Industry
Inner Mongolia	0.761	0.521	0.774	Tertiary Industry
Ningxia	0.520	0.543	0.668	Tertiary Industry
Qinghai	0.750	0.531	0.703	Tertiary Industry
Shandong	0.620	0.639	0.766	Tertiary Industry
Shanxi	0.441	0.894	0.776	Secondary Industry
Shaanxi	0.476	0.666	0.861	Tertiary Industry
Shanghai	0.562	0.795	0.977	Tertiary Industry
Sichuan	0.515	0.533	0.832	Tertiary Industry
Tianjin	0.410	0.666	0.643	Secondary Industry
Xinjiang	0.486	0.769	0.870	Tertiary Industry
Yunnan	0.588	0.673	0.864	Tertiary Industry
Zhejiang	0.499	0.620	0.911	Tertiary Industry

III. The Relationship Between Energy Consumption and Industrial Structure

The above analysis indicates that there are obvious differences in energy consumption among different industries. The regional disparities in industrial structure will result in differences in regional energy consumption, which could affect the sustainable energy development. In this context, based on the data on total energy consumption and industry output value from 2015 to 2019, the grey relational analysis is applied to calculate the grey relational coefficient for each industry in each province of China to study the relationship between energy consumption and industrial structure.

(1) Determine the reference sequence. Suppose the reference sequence is denoted as: $x_0 = \{x_0(1), x_0(2), ..., x_0(n)\}$, the comparison sequence is denoted as: $x_i = \{x_i(1), x_i(2), ..., x_i(n)\}$, $i = 1, 2, ..., m$.

(2) Normalize indicators. The dimensionless method is applied to original data.

(3) Calculate the grey relational coefficient. The normalized sequence $x_0 = \{x_0(1), x_0(2), ..., x_0(n)\}$ is regarded as the reference sequence; $x_i = \{x_i(1), x_i(2), ..., x_i(n)\}$, $i = 1, 2, ..., m$ is regarded as the comparison sequence. The associated sequence is calculated as

$$\xi_i(k) = \\ = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|},$$

where $i = 1, 2, \ldots, m$, $k = 1, 2, \ldots, n$, $\rho \in [0,1]$, generally $\rho = 0.5$.

Relational coefficient matrix is:

$$E = \zeta_{ik}\ (i = 1, 2, \ldots, m, k = 1, 2, \ldots, n).$$

(4) Calculate grey relational grade:

$$r_i = \sum_{k=i}^{n} w_i \xi_i(k).$$

Based on the calculation, we obtain the coefficients of specific impact of industrial structure on the energy consumption in each province in China and the industry with the greatest impact on energy consumption as shown in Table 3.

In general, the tertiary industry produces the greatest effect on energy consumption in China, followed by the secondary industry and the primary industry. Therefore, the energy consumption is largely determined by the share of tertiary industry. A change in the share of tertiary industry would greatly influence the reginal energy consumption. With a decrease in the contribution of primary and secondary industry to gross domestic product from 2015 to 2019, the contribution of tertiary industry increased during that period. The influence of the tertiary industry on energy consumption increased as well.

In most of the provinces in China, the share of tertiary industry influences the energy consumption. For these provinces, the focus should be put on optimising the internal industrial structure, reducing energy intensity, and developing energy-saving technologies. Besides, the energy consumption in three provinces (Henan, Shanxi, and Tianjin) is more affected by the share of secondary industry. For these three provinces, there is a possibility that the growing share of secondary industry will increase energy consumption. For this kind of provinces, certain measures should be taken to limit the growth of secondary industry and reduce the share of secondary industry. It is also necessary to promote the development of tertiary industry and improve its contribution to gross regional product. The economic development should be driven by the tertiary industry.

IV. Conclusion

China's economic development is currently in the late stage of industrialization dominated by heavy industry. The energy consumption of the sector Industry accounts for a large proportion of the total energy consumption. The share of the sector Industry in the consumption of primary energy sources is also large. The consumption of coal and crude oil is concentrated in the industries associated with mining, processing and conversion of energy within the sector Industry. While natural gas and electricity are used in part for energy conversion and basic supply, the rest of the demand is concentrated in the industries related to manufacture of metals or minerals and manufacture of chemical raw materials and chemical products. With regard to the other kinds of energy, for example, coke, the sector Industry consumes almost all of it. The demand for gasoline, kerosene, and diesel oil in the sector Industry is relatively low. The sector Industry and the sector Transport, Storage, and Post are the main consumers of fuel oil. In the sector Industry, energy demand is mostly concentrated in the heavy industries, except for the condition where the sector Industry does not have a significant demand for certain energy.

Since energy consumption obviously differs for different industries, the regional disparities in industrial structure can result in differences in regional energy consumption. The energy consumption in China is most likely to be affected by the tertiary industry followed by the secondary industry and the primary industry. Furthermore, the energy consumption tends to be influenced by a change in the share of tertiary industry. In addition, energy consumption in most of the provinces in China is greatly influenced by the share of tertiary industry. It is crucial to optimize the internal industrial structure, reduce energy intensity, and develop energy-saving technologies in these provinces. Some provinces, however, are affected by the share of secondary industry. Therefore, measures should be taken for this kind of provinces to reduce the share of secondary industry and improve the contribution of tertiary industry to gross regional product.

References

[1] Z. N. Lu, "An empirical analysis of industrial restructuring on China's energy consumption," *The journal of Quantitative and Technical Economics*, no. 12, pp. 53–55, 1999.

[2] X. H. Shi, L. Liu, "A study of the relationship between regional energy consumption and industrial structure in China," *Journal of China university of geosciences*, vol. 14, no. 6, pp. 39–47, 2014.

[3] X. Zou, P. Wang, "Study on the mechanism of industrial structure adjustment on the optimization of energy consumption structure," *RuanKeXue*, vol. 22, no. 5, pp. 11–16, 2021.

[4] F. Krausmann, H. Haberl, "The process of industrialization from the perspective of energetic metabolism: Socioeconomic energy flows in Austria," *Ecological Economics*, vol. 41, no. 2, pp. 177–201, 2002.

[5] Amir B. Ferreira Neto, Fernando S. Perobelli, Suzana Q. A. Bastos, "Comparing energy use structure: An input-output decomposition analysis of large economies," *Energy Economics*, vol. 43, pp. 102–113, 2014.

[6] S. J. Huang, Q. Li, J. Wang, "A comparative evaluation on different ownership industrial enterprises' efficiency in China," *Journal of Hebei University of Economics and Business*, vol. 38, no. 3, pp. 72–79, 2017.

[7] G. L. Li, Q. Fu, Y. Sun, "Grey relational analysis model based on weighted entropy and its application," *Journal of Water Resources and Water Engineering*, no. 6, pp. 15–18, 2006.

Liu Xueyao received the Master's degree in Economics from the Belarusian State University in 2021. In the same year, she was sponsored by the China Scholarship Council to study for a doctorate in the Belarusian State University. Her research interests include the studies on green economy, sustainable energy development, and low carbon development.

Alternative Possibilities of Using Electric Cars in Siberia

O.S. Kuznetsova*, V.V. Khanaev

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia.

***Abstract* — The ever-increasing demand for electricity requires constant expansion of generation facilities capable of providing the quantity and quality of energy supplied to the consumer. The search for highly efficient and more productive technological solutions in the field of electricity production and storage through distributed generation is one of the main lines in the development of the electric power sector. In turn, the wider use of such technologies, their advancements and improvements in their quality create the need to assess the potentialities and prospects for the use of various types of electrical energy storage and the related technologies required. The paper addresses the possibility of using electric vehicles as a battery for a small solar power plant.**

***Index Terms*: electric power industry, solar power plants (SPPs), renewable sources, electric vehicle, battery.**

I. Introduction

Nowadays, there is a steady upward trend in the number of private power generation facilities. A direct consequence of this is an increased interest in various storage devices that can boost the productivity and efficiency of solar power plants (SPPs). The possibility of regulating and controlling electricity consumption rates can lead to a sharp increase in prices for electricity, which may result, for example, in its unavailability for private households, which use electricity to meet most of their needs.

One should also consider the possibility of levelling tariffs with the removal of the regions with low electricity costs from their preferential position in the field of electricity supply, which will also negatively affect the private sector, which, owing to low prices, makes maximum use of electricity supply resources. The problems with gasification are also worth mentioning. For example, the Irkutsk region, being one of the main gas suppliers, does not have access to this resource and has to use electricity for heating purposes. Any changes in this area can be disastrous for most of the population [1].

One of the best solutions to smooth out possible energy shortages is self-generation, for example, with SPPs placed in the territories of private households, which will enable them to compensate for the lack of «centralized» electricity. Thus, the use of solar power plants by the private sector in most regions of Russia can not only improve the environmental situation but also help balance the consumption behavior or make it cost-effective. This solution can be very promising for the territories where tariffs currently allow the installation and operation of SPPs with a payback period of up to seven years for objects of about 100 m^2 of living space.

However, due to the vast territory of our country, the distribution of the solar energy across it varies greatly. The territories with the highest insolation indicators and relatively high daylight hours in the Russian Federation are the Republic of Buryatia and the Irkutsk Region, which theoretically allows the efficient operation of the SPP. Thus, one of the most common electricity generation solutions for private households in these areas is solar power plants.

With the insolation data taken into account when planning the infrastructure changes, a significant increase in generating capacity directly at consumers can be achieved. Analysis of potential efficiency, development and modernization of SPPs in the future may lead to an increase in their number in the region, which will reduce the negative effect of electricity generation at its constantly increasing values.

However, one of the main obstacles to commissioning solar power plants in the territory of private households is the need to store electricity due to the variability of solar insolation.

Problems arise in the energy storage technology due to the uneven energy reaching the solar panels. Therefore, solar panels are used either in conjunction with energy

* Corresponding author.
E-mail: oliv.smith@bk.ru

http://dx.doi.org/10.38028/esr.2022.03.0007
Received October 10, 2022. Revised October 19, 2022.
Accepted October 29, 2022. Available online December 5, 2022.

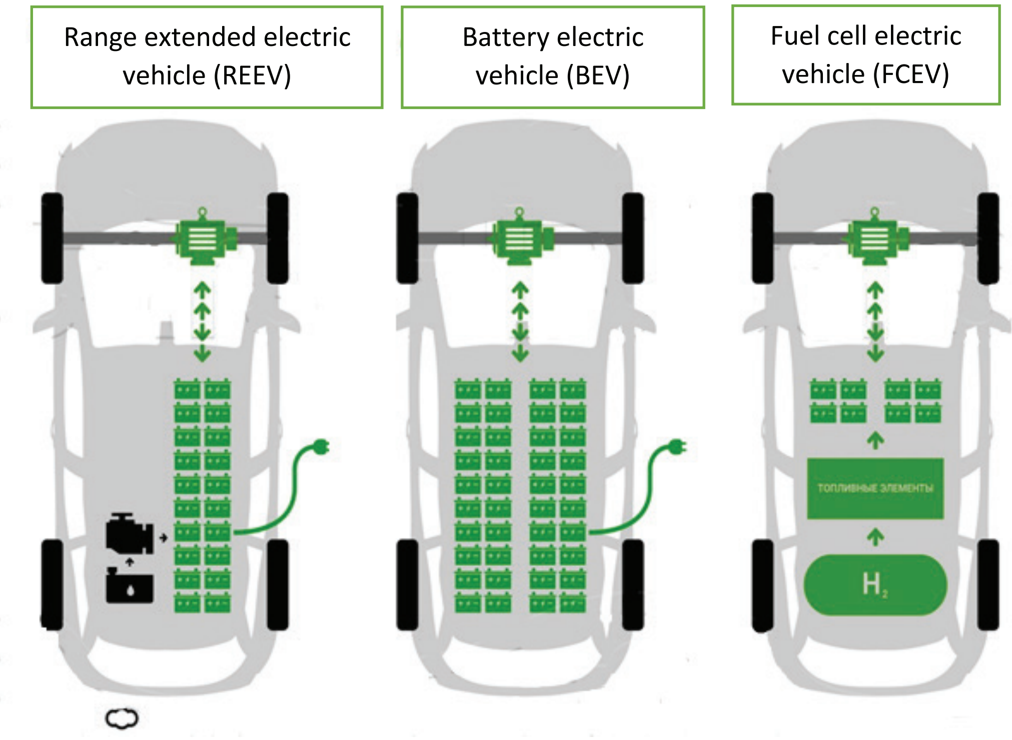


Fig.1 Types of electric vehicles.

storage or as an additional source of power supply for the main power plant.

II. Electric vehicles and their characteristics

In parallel with the ever-growing interest in various renewable energy sources, the demand for more environmentally and cost-effective modes of transport is increasing. Such types of transport include hybrid cars or electric vehicles, which are completely independent of traditional fuels and use electricity as the main energy resource for movement. The storage system of electric vehicles can be used for the accumulation and storage of electric energy in the sector of private households.

The mass use of electric vehicles, due to the need to resolve the environmental issues in large cities by reducing the harmful emissions from vehicles, could contribute to coping with the night-time dips in the electrical load curves.

Currently, the automotive industry tends to switch from internal combustion engines (ICE) to an electric motor. In October 2016, the German Bundesrat adopted a resolution banning the production of cars with internal combustion engines from 2030 [8]. Such a ban is also discussed in Norway and the Netherlands. This initiative can change the attitude of the world to harmful emissions and reduce the greenhouse effect in the future. In this regard, the development of ground electric transport and the use of cars with an electric motor instead of an internal combustion engine are relevant issues.

Therefore, the improvement in the battery charging process in ground electrically driven vehicles is relevant. Currently, there are six main engine systems:

1. A gasoline car runs on the fuel burnt in an internal combustion engine, which is followed by conversion of chemical energy into mechanical energy, which makes the car move.
2. A hybrid electric vehicle (HEV) operates using an electric motor powered by batteries in parallel with a gasoline engine receiving fuel from the gas tank. Batteries cannot be charged from external sources, and the mileage of a car using electric traction is extremely limited.
3. A plug-in hybrid electric vehicle (PHEV) has several types:
   - Parallel PHEV, which combines the operation of electric and gasoline engines, allowing battery charging from the grid and traveling a sufficiently long distance with electric traction motor solely.
   - Series-parallel PHEV, which is capable of operating either as a series or a parallel hybrid vehicle with an electric motor being the main drive.
4. Range-extended electric vehicle (REEV) known as series HEV with all the motive power provided by an electric motor, but with a small ICE present to generate additional electric power. The battery of this type of cars can be charged from the power grid.
5. Battery electric vehicle (BEV) is driven by an electric motor, which is powered by the energy of rechargeable batteries charged from external energy sources.

Table 1. Technical characteristics of batteries for leading manufacturers

Make/Model	Technical specifications				
	Number of charge cycles	Power reserve, km	Battery capacity, kWh	Maximum speed, km/h	Engine power, hp
Tesla Model *	10 000/15 000	644	100	267	362
Nissan LEAF E	5 500	550	60	156	217
Renault Megane E-Tech Electric	6 000	450	60	160	218
Ford Mustang Mach-E	8 500	450	75.7	180	258

* averaged data on Tesla models developed in 2016-2021 (100D, P100D, Performance, Long Range Plus, and Plaid).

6. Fuel cell electric vehicle (FCEV) converts hydrogen into electrical energy, which makes the car move. This happens in a stack of fuel cells, each of which is an electrochemical generator inside which a reaction occurs in which hydrogen is oxidized and generates energy. The electric energy produced feeds the electric motor and other systems of the car, and the battery pack is charged through regenerative braking.

For a long time, the development of electric vehicle transport has been hindered by the lack of suitable batteries (cheap, reliable, capacious, and environmentally friendly). Widespread sulfuric acid batteries, having a large mass, reduce the payload capacity of an electric vehicle, and an increase in their production and the need for recycling increases the environmental impact.

The weakest link is the number of charge/discharge cycles of electric vehicle batteries. This is due to their limited resource and increased charge/discharge-related load compared to the normal mode of operation.

Therefore, to assess the possibilities of battery charge/discharge cycles, a sample of the newest models of the major representatives of the electric car manufacturers (Tesla, Nissan, Renault, and Ford) was considered. These automakers conduct numerous studies on the development areas and innovative technologies, which contribute to the development of the automotive industry.

The main criterion for selecting the models of electric vehicles was the use of the battery as the main source of energy. For the selected models (Table 1), the technical characteristics and features of the charge system operation were analyzed [2-5].

A distinctive feature of the Tesla Model * electric car is a relatively large battery capacity, thanks to which it has a maximum power reserve. This is a significant competitive advantage because the main disadvantage of electric cars is their long charging time and small power reserve.

The Nissan Leaf is built on the new Nissan V platform, which is also used in the Juke crossover and the subcompact Micra 2011. An electric motor with a capacity of 80 kW (about 109 hp) and a torque reaching 280 Nm is located under the hood.

The electric vehicle has a front-drive wheel. The low location of the heaviest component (the battery) of the car provides better stability compared to traditional cars of this class. In addition, the battery also ensures higher structural rigidity for five-door hatchbacks of such a design.

A full cycle of charging batteries from a utility grid with a voltage of 220 V and a current of 12 A lasts about 9 hours. A special Nissan charger replenishes 80% of battery's charge (480 V — 125 A) in 30 minutes. The car can be equipped with two sockets for chargers in the front of the car: one for standard and the other for accelerated charging [6].

Currently, batteries are assembled at Nissan's facilities in Japan producing annually about 65 thousand sets. In 2012, as part of its project to start mass production of electric vehicles, Nissan opened a battery plant in Smyrna (Tennessee, USA) with a design capacity of 200 thousand sets per year.

Most cars, even hybrids, generate tons of CO_2 emissions every year. The Nissan Leaf is a fully electric car producing no harmful exhaust emissions. This electric car is not designed for long trips, but it has proven itself to be efficient in a megalopolis. Nissan has developed its application for mobile telecommunications devices, which finds the nearest charging station and filters out the stations that are already occupied or have high-power DC charging devices.

The next electric car included in the sample is the Renault KANGOO Z. E. This model was created mainly for the business environment. Several types of cargo bay partitions make it easy to transport loads of various sizes.

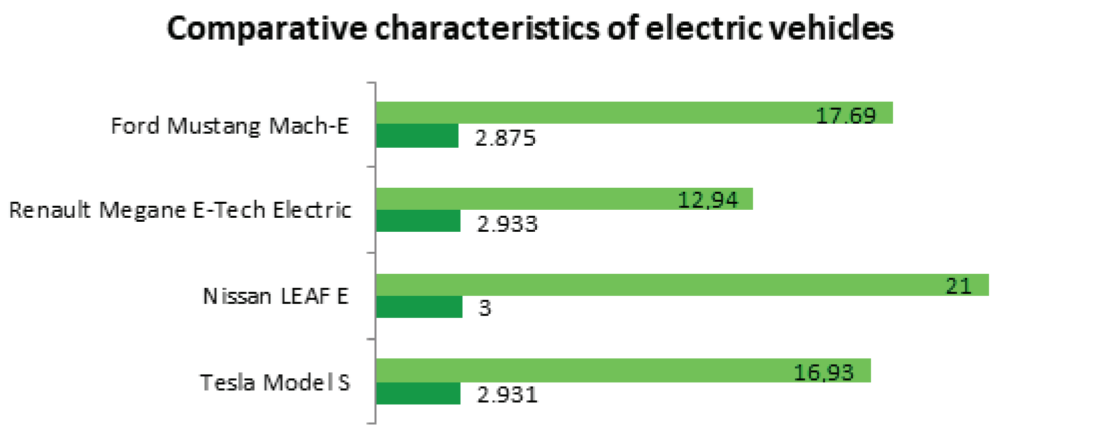
A distinctive feature of Renault is the «Chameleon» smart charging system, which allows charging the car from sockets of any power.

Ford Focus Electric was chosen as the latest model to be analyzed. The electric car is distinguished by its reliability and practicality. Ford prefers to use a battery with active liquid cooling and heating, which ensures stable battery operation over a wide range of temperatures.

The electric vehicle can be recharged from a DC power source at a voltage of 120 V, 240 V. The model is equipped with a 6.6 kW charger, which allows charging an electric car faster than the main competitor, Nissan Leaf. With the DC used, the charging power can reach up to 50 kW [5].

Nissan Leaf 2020 is the most popular electric car in Russia. It was chosen by 83% of Russian electric motorists. To date, the number of the cars used in Russia is 5.2 thousand.

The analysis focused on electric vehicles with the best characteristics, which were selected from different segments. Since electric car models are in different price



	Tesla Model S	Nissan LEAF E	Renault Megane E-Tech Electric	Ford Mustang Mach-E
Electricity consumption per 100 km, kWh	16.93	21	12.94	17.69
AB charge rate, kW/h	2.931	3	2.933	2.875

Fig.2 Comparative characteristics of electric vehicles from different segments.
The analysis of the diagram presented in Fig. 1 suggests the following conclusions:
- ***the most economical electric car is Renault KANGOO Z. E.;***
- ***the electric car with the highest charge rate is Nissan Leaf;***
- ***the electric car with a maximum battery capacity is Tesla S 85.***

categories and are designed for different tasks, comparison by absolute values of indicators cannot be objective. To ensure the objectivity and visibility of the study, a system of generalized relative indicators was proposed (Fig. 1). The following main indicators were considered for comparison:
- electricity consumption per 100 km in [kWh];
- battery charge rate in [kW/h].

The expansion of a set of tariffs and services mutually provided by the energy system and consumers requires the specialized recording equipment, i.e., advanced technologies for metering electricity consumption. Apart from the stricter requirements for metering devices, requirements are also increasing for systems for collecting, transmitting, and processing information obtained with their help (speed, accuracy, visualization, etc.). Technologically, the process of load management is in many ways akin to modern technologies providing communication services. It also requires consideration and establishment of tariffs for the minimum possible time intervals, instant information exchange between its participants (subscribers) and the availability of opportunities to provide related services in terms of the main objectives.

In general, the serial electric car of the future is a direct analogue of a modern city car, i.e., a comfortable vehicle with an average engine power of about 50 kW and a price of about USD 15 thousand or RUR 450 thousand (exchange rate of October 2021). The unit cost of power of the electrical vehicle will be about RUR 9 thousand/kW (USD 0.3 thousand/kW). The mass introduction of electric vehicles will be facilitated by such factors as the price of fuel for internal combustion engines and the environmental situation in places of compact and crowded residence. This suggests that autonomous electric transport will be recognized and widely developed and, possibly, by 2030, will account for a significant part of the total vehicle fleet.

Based on the studies of the technical characteristics of modern electric vehicles and their batteries, we will consider the theoretical possibility of their introduction and use as intermediate storage devices for SPPs in Siberia.

III. Alternative ways of using electric vehicle batteries

Solar power plants (SPPs) can be considered the most promising and evolving energy source in the territory of Siberia. This renewable source has several advantages. One of them is environmental safety at the place of generation, which is an important factor when choosing this type of generation from all possible renewable energy sources currently on the market. Geographical location and climatic features also play an important role when choosing a source of generation. The picture of the solar energy distribution is very diverse due to the vast territory of our country. The areas with the highest insolation indicators and relatively high daylight hours in the Russian Federation are the Republic of Buryatia and the Irkutsk Region, which implies efficient operation of the solar power plants here.

Thus, due to the favorable geographical location, the sunshine duration in the area at issue is 2000-2400 hours per year and the solar radiation intensity varies from 4 to

Table 2. Daily energy consumption in the household.

Power consumer	Quantity	Power, W	Operating time	Electricity consumption, kWh/day	Daily consumption total, kWh
Energy-saving bulbs	20	15	6	1.8	1.8 (1%)
Electric stove	1	8000	2	16	19.8 (9%)
Refrigerator	1	350	6	2.1	
Kettle	1	1500	0.4	0.6	
Microwave	1	1500	0.2	0.3	
Kitchen appliances	1	1600	0.5	0.8	
TV	1	100	5	0,5	5.85 (2%)
Computer	1	250	5	1.25	
Iron	1	2400	0.143	0.34	
Washer	1	1500	0.215	0.32	
Vacuum cleaner	1	2000	0.07	0.14	
Charging the phone	1	300	8	2.4	
Hairdryer / electric shaver	1	1800	0.5	0.9	
Electric boiler	1	8500	24	204	204.6 (88%)
Circulation pump	1	50	12	0.6	
Total volume per day	232.05 (100%)				

4.5 kWh/m2 a day.

Given the received insolation data when planning the infrastructure changes in construction and electricity generation, a significant increase in generation capacity for consumers or in so-called distributed generation can be achieved. Analysis of potential efficiency, development, and modernization of SPPs in the future may lead to an increase in their number in the region, which will reduce the negative effect of electricity generation at its constantly growing values.

After analyzing the insolation data obtained from publicly available sources, an abstract electricity consumer was taken as a basis for the research to theoretically design and calculate the number of necessary SPPs in the selected area and possible power to be generated from them.

A household with an area of 100 m2 was taken as a calculation unit, which was determined based on the ever-growing demand for residential facilities in the private sector. The calculation of the electricity consumed considered both the minimum required set of electrical appliances used by an electricity consumer and their approximate operating time (Table 2). The study relied on the averaged values considering the changes in the consumption depending on the change of the season. The electricity consumed to boil water and heat the room, as well as the operating time of electrical appliances are also taken into account.

The total daily volume of electricity consumed by a household with an area of 100 m2 is approximately 232.05 kWh, of which 204.6 kWh is used for the needs of the boiler and pump. The electricity consumption for household needs amounted to 25.65 kWh, and about 1.8 kWh of electrical energy was used for lighting. Thus, when using an electric vehicle as a backup battery device, some household needs can be covered or EV power reserve can be used as a power source in case of emergency disconnection of the main battery.

The highest load values are associated with the operation of the boiler. This load requires the investment in storage and is a variable value depending on the season. The load corresponding to lighting and household needs, being a relatively constant, is flexible and is most subject to modernization through the introduction of SPPs.

The conducted studies confirm once again that it is impossible to fully provide the household with electrical energy from a SPP without using a battery. Since the average vehicle is not used around the clock and not every day, electric cars can be used as a backup storage device capable of supplying power at least for lighting and some other household needs, and even for some household electrical appliances, under optimal operating conditions of SPP panels and rational and economical energy use.

The main parameter, which affects how the planned loads are covered, is the solar panel capacity to be chosen. Thus, the calculation used the average amount of electricity generated for the Irkutsk region and the Republic of Buryatia, considering the choice of three different solar panels with the same coverage area of 10 m2. When installing solar panels at an optimal angle for the area or models of the panels that adjust the tilt angle automatically, it is possible to fully cover the electricity used for lighting or even have more electricity than the lighting needs. Thus,

Table 3. Data on power generation for solar panels of various capacities.

Solar battery SilaSolar, W	250	350	450
January	4.02	4.69	6.03
February	5.67	6.62	8.51
March	7.68	8.96	11.52
April	7.59	8.86	11.39
May	7.28	8.49	10.98
June	6.75	7.88	10.13
July	6.34	7.15	9.20
August	5.99	6.98	8.98
September	5.84	6.81	8.75
October	5.07	5.92	7.61
November	3.92	4.57	5.87
December	3.30	3.85	4.95
Average annual electricity generation, kWh/day	5.77	6.73	8.65
Total electricity generation per year of operation, kWh	2 104.44	2 455.18	3 156.66

it can be assumed that the panel with the highest calculated output will generate electricity to cover not only the lighting needs, but also the load of some electrical appliances. The calculation data are shown in Table 3.

The values obtained from [7] were used to calculate and obtain the predicted values of the required additional generating capacities.

The calculation results included the values of the total amount of electricity consumed, the amount of electricity consumed for lighting needs, and their overall annual values.

One of the main conclusions of this study is that the proposed solution to the problems may be partial replenishment of electricity from renewable resources, which will mitigate the economic and environmental situation. SPP as a source of additional generating capacity, used to partially meet the needs of private sector, can become one of the promising and efficient solutions. Despite the low electricity tariffs in the Irkutsk region and the Republic of Buryatia, their territories are favorable for the introduction of SPPs due to their geographical location.

When determining the effectiveness of load management, one should avoid its direct opposition with the increase in generating capacity and consider both of these measures as a reasonable and balanced complement to each other. The construction of new generating capacities and load management, when considered jointly, allow:

optimizing the degree of loading, extending the service life of the existing generating and power grid equipment, and reducing the construction costs of new one;

- optimizing the energy equipment repair schedules;
- reducing the cost of maintaining inefficiently loaded generating capacities in good operational condition;
- optimizing the number of production personnel;
- increasing the stability of the electric power system in the case of external disturbances and accidents;
- allocating funds for technical re-equipment of the electric power industry instead of forcibly applied half–measures (upgrades and repairs).

In the event of a change in the initial prerequisites or economic situation, the timely application of load management can reduce the risks of investment in the development of the electric power industry. This is because the optimization of power consumption schedules due to the capabilities of consumers reduces the likelihood of a shortage or lack of demand for newly introduced power capacities in case of unexpected, relative to forecast, changes in power consumption.

Conclusion

The analysis of the capabilities and characteristics of the updated models of electric vehicles from several largest manufacturers and calculations made for a private household, whose energy needs are fully or partially met with the help of solar electric panels suggest the conclusion that it is advisable to use an electric vehicle storage system as an additional or backup battery. The energy stored in this way will be enough to meet the needs of lighting. The ever-growing competition between manufacturers of electric vehicles accelerates the development of methods for increasing the capacitance characteristics of batteries, engine power, charge rate and mechanism, power reserve, and the number of charging cycles. There are very few studies in this area in our country at present, which makes it more difficult to incorporate modifications into existing projects or those under development.

References

[1] O.S. Kuznetsova and V.V. Khanaev Prospects for the use of solar energy in the Irkutsk Region and the Republic of Buryatia [Online]. Available at: https://doi.org/10.1051/e3sconf/202128905002 (accessed: 25.08.2021).

[2] Main characteristics and charging methods of the Tesla Model S electric car [Online], *Official website of Tesla Motors*. Available at: https://www.tesla.com, (accessed: 08.28.2021).

[3] Main characteristics and charging methods of the Nissan Leaf electric car [Online], *Official website of Nissan Motor Co., Ltd.* Available at: https://www.nissanusa.com/electric-hybrid-cars (accessed: 08.28.2021).

[4] The main characteristics and methods of charging the electric car Renault KANGOO Z. E. [Online] / *The official website of the Renault Group.* Available at: https://www.renault.ru/vehicles/range/kangoo-ze.html (accessed: 08.28.2021).

[5] The main characteristics and methods of charging the Ford Focus Electric electric vehicle [Online], *The official website of Ford Motor company.* Available at: https://www.ford.com/cars/focus/2017/models/focus-electric, (accessed: 08.28.2021).

[6] Filkina A.N. Creation of hybrid cars as one of the directions to solve the problems of ecology in large cities. A*dvances in Current Natural Sciences.* 2004. No. 11. pp. 45-46.

[7] Limarev A.S., Kovalenko A.O., Ochkova E.A., Akmanova Z.S. Evaluation of the feasibility of using electric motors on electric vehicles in modern conditions. *Proceedings of NAMI* .2015. No.263. pp. 132-139.

[8] *Official website of the US National Renewable Energy Laboratory.* [Online]. Available at: https://www.nrel.gov (accessed 20.05.2020).

[9] Development of proposals on the prospects for the development of the Russian electric power industry for the period up to 2030, *Scientific Report. Stage 1.* Building the options and scenario conditions for the development of the country's electric power industry until 2030. ESI SB RAS, 2008. 201 p.

Evolution of Energy Systems Research: Analysis of Documents Co-citation Network

A.V. Mikheev*

Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

***Abstract*— The bibliometric overview investigates the evolution in the field of energy systems research over scientific publications in the Scopus database during the last two decades - 2001-2021. The study reveals the underlying topic structures derived from research document co-citation network using clustering algorithm of CiteSpace software. The representation of the research front with identified key topics is the result of visual and topological analysis of the network. The topics discovered correspond to the emerging trends such as multidimensional integration of energy systems, including hybrid renewable systems and sector coupling, cybersecurity and resilience issues, and various technologies related to machine learning, energy storage, DC microgrids, and others.**

***Index Terms*—energy systems, power systems, innovation development, research trends, research agenda, bibliometric analysis, scientometric analysis, visual analysis, CiteSpace.**

I. Introduction

Global socioeconomic development has a significant impact on energy systems, on their control and management [1]. The transformation of energy systems at the beginning of the 21st century leads to a significant technological shift and expansion of new energy technologies for production, transport, accumulation, distribution, and consumption. First of all, the use of renewable energy sources and improved efficiency are crucial topics to provide cleaner energy for a sustainable future [2]. There is an increase in the complexity of the energy infrastructures operating the flows of energy, the coverage of horizontal connections, the combination of territorial-technological and temporary management [3]. The active use of information and communication technologies fundamentally changes the root properties of energy systems. The systems become human-machine (cyber-physical) systems, interacting with the width of the network of power facilities, distributed over a large area, and functioning with a single connection of reliable and affordable power supply [4]. Understanding the future envision of the energy systems through strategic forecasting of the innovative development of the economy is a difficult and complex challenge.

On the other hand, it is possible to use intelligent and computational tools based on big data analysis to support research and respective managerial activities. One of such promising approaches is a bibliometric analysis of the documents as codified knowledge (research articles, technology patents, analytical reports, etc.) related to the R&D sector. There are a lot of publications that implement scientometric approaches to review the issues of wide-range energy systems.

Many systematic bibliometric reviews in recent decades show strong interest in energy systems. A bibliometric analysis of development knowledge on multienergy systems, microgrids and Smart Grids, based on more than 20,000 articles from the Web of Science [5]. The paper [6] provides a comprehensive overview of the results of two decades of research and enables interested readers to obtain a comprehensive overview of the key trends in the energy systems analysis (ESA).

Several reviews analise energy research focusing on certain countries at the national level such as renewable energy in Turkey [7], energy sector in Spain [8].

This article continues the bibliometric research on the development of energy systems, started in the previous work [9]. The key contributions of this paper in the field of energy systems are a representation of state-of-the-art technology and visualization of the topics of research front over the document co-citation network. This paper

* Corresponding author.
E-mail: avmiheev@gmail.com

http://dx.doi.org/10.38028/esr.2022.03.0008
Received June 28, 2022. Reviewed August 8, 2022. Revised September 12, 2022. Accepted October 18, 2022.

considers a holistic perspective rather than focusing on a specific issue or area.

The approach used in the paper is one of the critical components of an intelligent decision support system in the field of strategic and innovative development of the energy sector, including understanding the interrelationships of the main thematic areas and predicting future research directions.

II. Methodology and tools

The basis of the methodology in this article is the statistical and textual analysis of bibliometric data (metadata) of an array of scientific publications in line with the concept of "big data".

The general workflow of this analysis includes several sequential steps:

1. Retrieval of publications data related to a specific problem or knowledge area.
2. Data cleaning manually or automatically to remove irrelevant publications.
3. Scientometric quantitative analysis applying various metrics like betweenness centrality to construct different co-occurrence networks. Network examples are co-authorship networks, co-word networks, co-terms networks, co-citations networks, and others. Further clustering analysis of constructed networks is also an important part of the scientometric approach.
4. Visualization of the knowledge domain and in-depth analysis to obtain the status quo of research, discover emerging trends, hidden interrelations, and other valuable outputs.

In this article, we use CiteSpace, a Java-based scientometric software package developed by Chaomei Chen, to create and visualize bibliographic record networks [10]. CiteSpace is intended for a systematic review of the scientific literature and is widely used in scientometric studies [11, 12]. CiteSpace supports a complete analytical process for visualizing and analyzing research trends and patterns in the scientific literature [13, 14].

The structure and dynamics of the literature can be analyzed in terms of a co-citation network derived from citations generated by citing articles [15]. CiteSpace uses both base documents imported from Scopus and documents obtained from the bibliographic lists of these documents to construct a network. Additionally, the document co-citation network can be decomposed into different clusters of closely related links to represent research topics [16]. These clusters can then be labeled a set of the terms extracted from the titles of the most representative citing articles for each cluster. Each cluster found within the co-citation network weighted on a time scale, represents a common research topic that is relevant in a certain period. In this way, the evolution of the key topics in the certain field can be investigated to identify the global research trends.

III. Data

The study was based on a set of scientific documents related to the field of energy systems. The Scopus International Science Citation Index database was used as a source of bibliographic metadata as in [9]. The Scopus database contains a large number of documents and has a convenient interface and API to export necessary metadata in Scopus CSV format. A search was carried out in the database using the phrases “energy system” and “power system”. The Scopus search engine automatically merges both the single and plural forms of the ‘system’ noun.

The constructed query selects research publications of document type as “Article” and “Review” from reviewed and trusted journals. Documents of type “Review” were chosen to build more consistent co-citation network. The main language of the documents is English only. Documents within the period 2001–2021 were considered since the observed growth of scientific publications.

To avoid including irrelevant documents, for example, from medical science, the search results were filtered to remove the subject areas far from “Energy” like “Medicine”, “Nursery”, “Computer Science”, “Arts and Humanities”, etc. On the other hand, since “energy” is a multidisciplinary topic, subject categories such as “Engineering”, “Chemistry”, “Environmental Science”, “Social Science”, “Material Science”, etc. remain under consideration.

The exact query text of advanced document search in Scopus is as follows:

```
TITLE-ABS-KEY ( "energy system*" OR "power system*" ) AND PUBYEAR > 2000 AND PUBYEAR < 2022 AND ( EXCLUDE ( SUBJAREA,"BIOC" ) OR EXCLUDE ( SUBJAREA,"MEDI" ) OR EXCLUDE ( SUBJAREA,"ARTS" ) OR EXCLUDE ( SUBJAREA,"HEAL" ) OR EXCLUDE ( SUBJAREA,"PSYC" ) OR EXCLUDE ( SUBJAREA,"NEUR" ) OR EXCLUDE ( SUBJAREA,"PHAR" ) OR EXCLUDE ( SUBJAREA,"NURS" ) OR EXCLUDE ( SUBJAREA,"IMMU" ) OR EXCLUDE ( SUBJAREA,"VETE" ) OR EXCLUDE ( SUBJAREA,"DENT" ) OR EXCLUDE ( SUBJAREA,"Undefined" ) ) AND ( LIMIT-TO ( LANGUAGE,"English" ) ) AND ( LIMIT-TO ( DOCTYPE,"ar" ) OR LIMIT-TO ( DOCTYPE,"re" ) )
```

The query search on November 26, 2021, gives a quite large dataset of 103,858 documents including 98,097 research articles and 5,830 reviews. The documents were successfully imported automatically through the CiteSpace. The dataset contains:

- 3,510,634 total references,
- 3,378,143 (96.0%) valid references,
- 251,217 unique keywords.

Fig. 1 (a) presents the publishing statistics over the retrieved documents by years. The diagram shows the exponential growth in publishing activity (blue curve). The orange columns together with the calculated polynomial trending brown line are the percentages of growth from year to year. Fig. 1 (b) shows the annual publishing

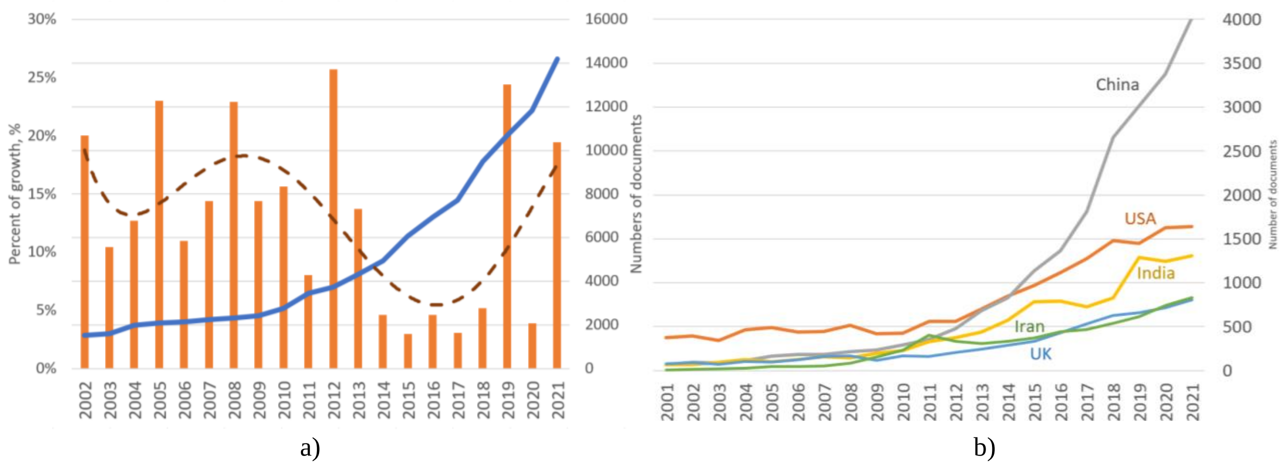


Fig. 1. Publishing growth on the field of energy systems research in the Scopus database in 2001-2021: (a) total number of documents by year (blue line) and annual growth (orange bars and dashed trend line); (b) publication activity of the top 5 countries by year.

activity of the five productive countries. The diagram represents a typical scientific publishing boom that started from the beginning of the 2010s in the world and especially in China. We see that the total annual contribution from China surpasses that of the USA and contributors from other countries since 2015.

IV. Analysis of the Document co-citation network

A weighted document co-citation network was built using CiteSpace software to analyze the evolution of research in the energy/power system field. CiteSpace's criterion for the selection to build the network is a general threshold based on the value of the g-index with expanding coefficient $k = 25$ (for more details, see [14]). This criterion delivers 2476 nodes representing research papers, and 10925 edges - citing links between them. Figure 2 represents the visualization of the network. Color indicates the year of publication relative to the timeline from 2001 up to 2021, and the size of the node depends on the number of citations. Due to significant growth of research activity, scientific publication, and citing practices as shown on Fig. 1 the density of the network is much higher for period 2011-2021.

Cluster analysis, applied to the constructed network, detects the main topics (clusters) to which the researchers was drawn. Each topic is characterized by a keyword profile, which is a set of specific terms obtained from the text information of documents (title, keywords, abstract) related to a specific cluster. All clusters are numbered in descending order of their sizes. Cluster labels are obtained from the titles of the papers using a log-likelihood ratio (LLR) weighting algorithm. The LLR algorithm is used to calculate and define a set of terms or keyword's profiles that represent the basic theme of each cluster of co-cited documents. On figure 2 only top terms of cluster keyword's profile are shown. In some cases, they could not reflect the actual topic of a particular cluster. Table 1 contains list of most frequent terms for each cluster. In general, these terms describe the topic together.

Based on the results of the cluster analysis of the co-citation network, the "hottest" topics of energy / power system research are observed. The two main branches are detected visually.

First, the strongest topic #0 "hybrid renewable energy system" represents the main research efforts of the last few years focused on effective solutions to implement renewable energy sources into conventional energy systems. Of course, topic #0 is very close to relating topics such as #12 "energy storage system" and #3 "integrated energy system". The stochastic nature of renewable energy sources requires the development of energy storage technologies to provide a reliable energy supply. "Integrated energy systems" is another promising concept for the flexible use of different energy sources and technologies. The next important topic in the research branch is #1 "sector coupling", which means combining energy-consuming sectors (buildings heating and cooling, transport and industry) with power generation. Sector coupling plays the important role in the context of decarbonization. The topics mentioned above have the ancestor topic #2 "heat roadmap Europe", which has a more informative label as "smart energy system" of the same weight. This topic began to be actively discussed in the late 2000s. The next topic #13 "energy justice" collects papers addressing to the socioeconomic issues and new market regulations that follow with the technological transformation of energy systems.

Second main research branch in Figure 2 is formed by four clusters: #5 "robust unit commitment", #7 "dc microgrid", #8 "electric vehicle", #11 "false data injection attack".

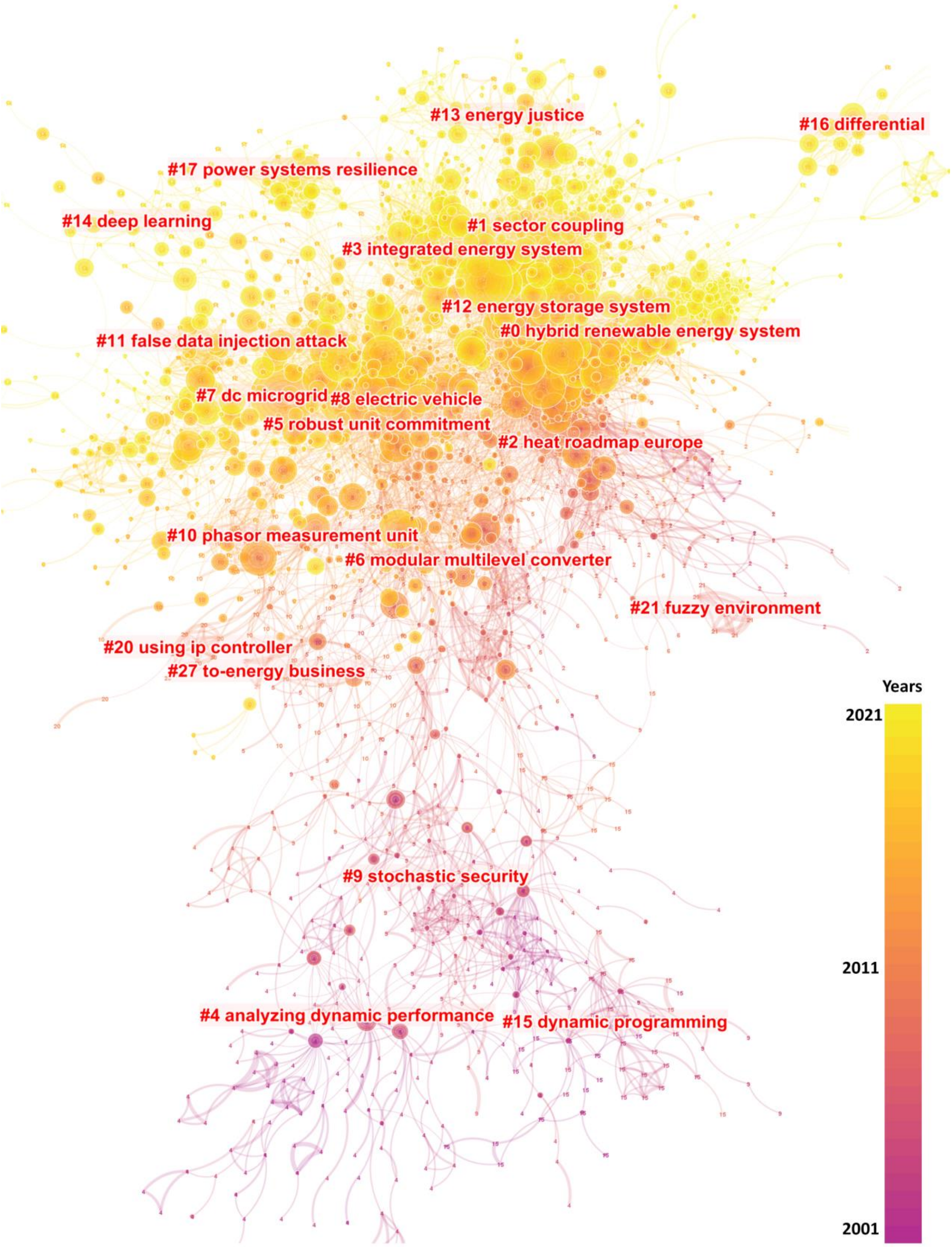


Fig. 2. Clusters with topic labels found on the document co-citation network.

Table 1. Cluster keyword profiles identified from document co-citation network in 2001 - 2021.

Cluster ID	Size	Silhouette	Mean year	Label (LLR)
0	200	0.919	2013	hybrid renewable energy system (66479.66, 1.0E-4); hybrid energy system (52691.74, 1.0E-4); case study (25715.16, 1.0E-4); renewable energy system (20119.44, 1.0E-4); techno-economic analysis (20020.19, 1.0E-4)
1	183	0.851	2015	sector coupling (21530.39, 1.0E-4); high share (15783.33, 1.0E-4); power sector (13901.89, 1.0E-4); energy system model (13493.96, 1.0E-4); hydrogen production (13243.51, 1.0E-4)
2	181	0.865	2007	heat roadmap Europe (7019.11, 1.0E-4); smart energy system (7019.11, 1.0E-4); large-scale integration (6854.62, 1.0E-4); energy system analysis (5501.04, 1.0E-4); life cycle (5434.42, 1.0E-4)
3	176	0.873	2014	integrated energy system (56565.28, 1.0E-4); multi-energy system (38993, 1.0E-4); energy hub (29611.42, 1.0E-4); energy system (23101.55, 1.0E-4); integrated electricity (20500.39, 1.0E-4)
4	173	0.995	1998	analyzing dynamic performance (4445.52, 1.0E-4); vector field (4445.52, 1.0E-4); parameter space (4445.52, 1.0E-4); controller design (3908.49, 1.0E-4); using normal form (3201.91, 1.0E-4)
5	158	0.873	2009	robust unit commitment (16387.49, 1.0E-4); unit commitment (15905.79, 1.0E-4); stochastic unit commitment (13278.1, 1.0E-4); wind uncertainty (10865.33, 1.0E-4); wind power generation (8874.34, 1.0E-4)
6	153	0.899	2007	modular multilevel converter (10225.39, 1.0E-4); wind energy conversion system (8300.53, 1.0E-4); grid integration (8026.56, 1.0E-4); reactive power control (7156.72, 1.0E-4); dc-dc converter (6702.55, 1.0E-4)
7	147	0.88	2013	dc microgrid (39370.32, 1.0E-4); virtual synchronous generator (31684.68, 1.0E-4); islanded microgrid (16861.55, 1.0E-4); weak grid (16559.39, 1.0E-4); stability analysis (13693.78, 1.0E-4)
8	128	0.808	2011	electric vehicle (41492.13, 1.0E-4); plug-in electric vehicle (21378.23, 1.0E-4); load frequency control (20115.16, 1.0E-4); smart grid (13442.44, 1.0E-4); quasi-oppositional harmony search algorithm (12717.23, 1.0E-4)
9	115	0.958	2001	stochastic security (2423.06, 1.0E-4); competitive electricity market (1835.85, 1.0E-4); ac constraint (1719.57, 1.0E-4); transmission system (1530.28, 1.0E-4); power systems operation (1215.97, 1.0E-4)
10	99	0.93	2008	phasor measurement unit (13746.54, 1.0E-4); gravitational search algorithm (9657.52, 1.0E-4); economic load (5584.26, 1.0E-4); artificial bee colony algorithm (4953.39, 1.0E-4); considering measurement redundancy (4558.35, 1.0E-4)
11	84	0.914	2013	false data injection attack (58164.37, 1.0E-4); smart grid (39959, 1.0E-4); cyber attack (22401.6, 1.0E-4); power grid (8392.18, 1.0E-4); data integrity attack (8116.37, 1.0E-4)
12	71	0.883	2013	energy storage system (19599.3, 1.0E-4); energy storage (18119.66, 1.0E-4); hybrid energy storage system (13705.2, 1.0E-4); energy storage technologies (11584.05, 1.0E-4); air energy storage system (11029.82, 1.0E-4)
13	60	0.956	2015	energy justice (9966.24, 1.0E-4); to-peer energy trading (9261.4, 1.0E-4); energy transition (9064.67, 1.0E-4); power system (3914, 1.0E-4); local electricity market (3531.15, 1.0E-4)
14	58	0.977	2016	deep learning (14204.23, 1.0E-4); machine learning (8584.87, 1.0E-4); deep learning model (6963.23, 1.0E-4); reinforcement learning (5034.53, 1.0E-4); deep reinforcement learning (4434.68, 1.0E-4)
15	55	0.976	2000	dynamic programming (774.48, 1.0E-4); traditional structure (689.64, 1.0E-4); enhanced adaptive lagrangian relaxation (647.56, 1.0E-4); economic load (633.93, 1.0E-4); generator planning (633.53, 1.0E-4)
16	32	1	2016	differential evolution (2623.51, 1.0E-4); incorporating stochastic wind (2472.89, 1.0E-4); solar generation (2472.89, 1.0E-4); facts device (2183.14, 1.0E-4); phosphoric acid fuel cell (2144.65, 1.0E-4)
17	29	0.997	2016	power systems resilience (2553.7, 1.0E-4); extreme weather event (2458.55, 1.0E-4); energy system resilience (1697.81, 1.0E-4); power system resilience (1678.57, 1.0E-4); resilience assessment (1613.58, 1.0E-4)
19	19	1	2012	wireless power transfer system (5914.99, 1.0E-4); inductive power transfer system (4391.08, 1.0E-4); wireless power transfer (1865.97, 1.0E-4); resonant converter (912.41, 1.0E-4); three-coil wireless power transfer system (796.6, 1.0E-4)
20	11	1	2006	using ip controller (372.53, 1.0E-4); two-area load frequency control (195.65, 1.0E-4); multi-area load frequency control (173.83, 1.0E-4); harmony search (129.97, 1.0E-4); PID controller adjustment (64.98, 1.0E-4)
21	7	0.999	2005	fuzzy environment (74.88, 1.0E-4); community-scale renewable energy system (49.51, 1.0E-4); uncertainty-an interval chance-constrained programming approach (49.51, 1.0E-4); regional energy system (32.59, 1.0E-4); multiple uncertainties (24.66, 1.0E-4)
27	4	1	2010	to-energy business (54.78, 1.0E-4); considering environmental constraint (27.05, 1.0E-4); power system (2.12, 0.5); smart grid (0.22, 1.0); case study (0.19, 1.0)

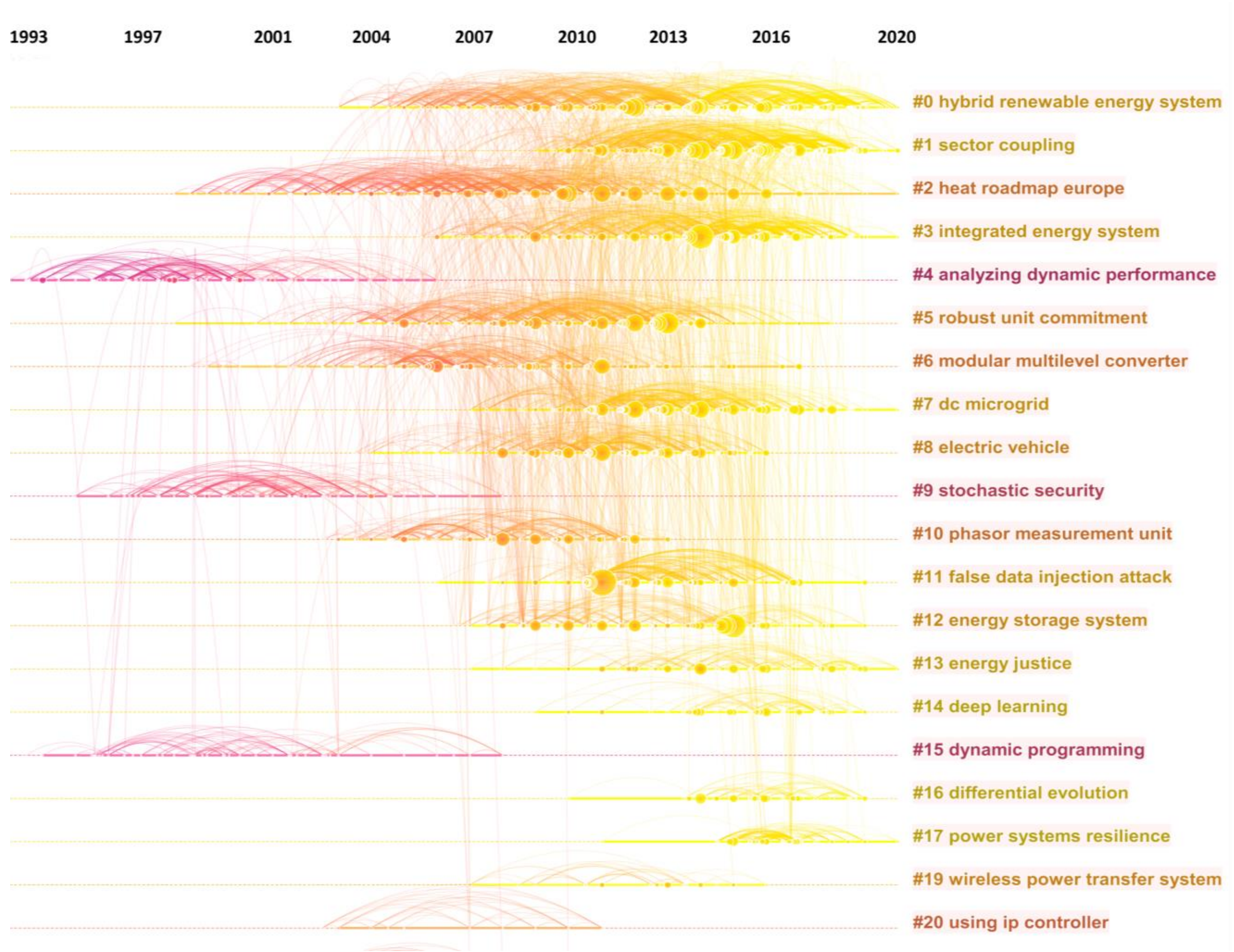


Fig. 3. Distribution of the topic clusters of the document co-citation network in the field of energy systems on the timeline.

In comparison with the first branch, these topics relate to the various advanced aspects of flexible and intelligent operation control in energy systems rather than development issues.

In addition, at the top of the network there are several separate topic clusters. These topics are more recent and, therefore, they have less citation impact. Cluster #14 "deep learning" reflects the relevance of using machine learning methods for adaptive intelligent control and management of electric power systems. #17 "power system resilience" is another important topic that highlights the increasing attention to the issue of system resilience during recent years.

The research frontier is clearly observed on the document co-citation network (Fig. 3). The frontier topics are colored yellow according to the colormap used.

Figure 3 summarizes the distribution of the detected topic clusters of the document co-citation network over the period considered. The timeline view of the revealed clusters represents the evolution roadmap of energy / power systems research. The sizes of the circles correspond to a number of future citations. The curves along and between the main cluster lines are inner citations and cross-topic citations.

It is important to investigate the majority of publications cited in the built document co-citation network as having the highest impact on the scientific community. These documents have citation bursts that reflect changes in trending topics. A citation burst indicates that the citations of an article increase rapidly over a period of time. Table 2 reports the 50 references with the strongest citation burstiness. References are ordered by the start year of the burst to track the evolution of research focus. In Table 2, the column "Year" refers to the year of publication. The values of the column "Strength" are calculated by the default Kleinberg algorithm of CiteSpace. "Begin" refers to the year in which the citation of a publication begins to burst. The "End" column contains the last year of a burst. The red zone on the line in the last column shows the placement of the citation burst over time period 2001-2021. The average duration between publication year and mean year of the citation burst is about 5,25 years. The average duration of the burst period is about 2,5 years.

Table 2. List of top 50 documents with the strongest citation bursts in 2001-2021.

References	Year	Strength	Begin	End	2001 - 2021
[17] Kundur P, 1994, Power System Stability and Control	1994	34.15	**2001**	2002	
[18] Sauer PW, 1998, Power System Dynamics and Stability	1998	34.06	**2001**	2006	
Hingorani NG, 2000, Understanding FACTS	2000	30.7	**2002**	2008	
Abur A, 2004, Power System State Estimation	2004	32.28	**2005**	2012	
[20] Ackermann T, 2005, Wind Power in Power Systems	2005	49.62	**2007**	2013	
[21] Lund H, 2005, Large-scale integration of wind power into different energy systems @ Energy, V30, P2402-2412	2005	34.77	**2007**	2013	
[19] Kundur P, 2004, Definition and classification of power system stability @ IEEE Trans Power Syst, V19, P1387-1401	2004	27.65	**2007**	2012	
[25] Blaabjerg F, 2006, Overview of control and grid synchronization for distributed power generation systems @ IEEE Trans Ind Electron, V53, P1398-1409	2006	26.46	**2007**	2014	
Bollen MHJ, 2006, Signal Processing of Power Quality Disturbances	2006	25.93	**2007**	2014	
[22] Carrasco JM, 2006, Power-electronic systems for the grid integration of renewable energy sources, V53, P1002-1016	2006	55.33	**2008**	2014	
[26] Pepermans G, 2005, Distributed generation, V33, P787-798	2005	28.27	**2008**	2013	
Akagi H, 2007, Instantaneous Power Theory and Applications to Power Conditioning	2007	28.2	**2008**	2015	
[24] Lund H, 2007, Renewable energy strategies for sustainable development @ Energy, V32, P912-919	2007	38.3	**2009**	2015	
Phadke AG, 2008, Synchronized Phasor Measurements and Their Applications	2008	49.59	**2010**	2016	
[23] Lund H, 2008, Integration of renewable energy into the transport and electricity sectors through V2G @ Energy Policy, V36, P3578-3587	2008	43.97	**2010**	2016	
[27] Chicco G, 2009, Distributed multi-generation, V13, P535-551	2009	34.26	**2010**	2017	
Shayeghi H, 2009, Load frequency control strategies, V50, P344-353	2009	31.9	**2010**	2017	
[35] Kempton W, 2005, Vehicle-to-grid power implementation, V144, P280-294	2005	28.38	**2010**	2013	
[28] Pal B, 2005, Robust Control in Power Systems	2005	25.36	**2010**	2013	
[30] Strbac G, 2008, Demand side management, V36, P4419-4426	2008	48.46	**2011**	2016	
[32] Tuohy A, 2009, Unit commitment for systems with significant wind penetration @ IEEE Trans Power Syst, V24, P592-601	2009	38.43	**2011**	2017	
Lund H, 2010, The role of district heating in future renewable energy systems @ Energy, V35, P1381-1390	2010	28.72	**2011**	2017	
Flourentzou N, 2009, VSC-based HVDC power transmission systems, V24, P592-602	2009	26.53	**2011**	2017	
[41] Rashedi E, 2009, GSA, V179, P2232-2248	2009	38.15	**2012**	2017	
Wang J, 2008, Security-constrained unit commitment with volatile wind power generation @ IEEE Trans Power Syst, V23, P1319-1327	2008	33.03	**2012**	2016	
[33] Zhou W, 2010, Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems @ Appl Energy, V87, P380-389	2010	26.8	**2012**	2016	
[29] Bevrani H, 2009, Robust Power System Frequency Control	2009	26.65	**2012**	2017	
[37] Chen H, 2009, Progress in electrical energy storage system, V19, P291-312	2009	44.61	**2013**	2017	
[36] Clement-Nyns K, 2010, The impact of charging plug-in hybrid electric vehicles on a residential distribution grid @ IEEE Trans Power Syst, V25, P371-380	2010	28.92	**2013**	2018	
Farhangi H, 2010, The path of the smart grid @ IEEE Power Energy Mag, V8, P18-28	2010	28.65	**2013**	2018	
[38] Beaudin M, 2010, Energy storage for mitigating the variability of renewable electricity sources, V14, P302-314	2010	28.16	**2013**	2017	
[34] Morales JM, 2009, Economic valuation of reserves in power systems with high penetration of wind power @ IEEE Trans Power Syst, V24, P900-910	2009	27.21	**2013**	2017	
[31] Palensky P, 2011, Demand side management, V7, P381-388	2011	25.87	**2013**	2019	
[40] Connolly D, 2010, A review of computer tools for analyzing the integration of renewable energy into various energy systems @ Appl Energy, V87, P1059-1082	2010	56.21	**2014**	2018	
Zimmerman RD, 2011, MATPOWER, V26, P12-19	2011	59.72	**2016**	2019	
Sun J, 2011, Impedance-based stability criterion for grid-connected inverters @ IEEE Trans Power Electron, V26, P3075-3078	2011	28.52	**2017**	2019	
[39] Hirsch A, 2018, Microgrids, V90, P402-411	2018	29.62	**2019**	2021	

In the beginning of the period the power system stability, dynamics and control were more attractive topics [17-19].

From the middle of the first decade the focus was shifted to renewable energy sources, especially wind power generation [20, 21]. The two main issues at this time are:

(1) Integration of renewable sources into electric power systems [21-23] to provide sustainable economic development [24];

(2) Coordination of distributed generation, including renewable sources, with operating conditions of the electrical power grid [25, 26]. The "distributed generation" remained a highly cited topic in the next decade [27].

In the 2010s, we can see several important topics from highly cited publications. On the one hand, there has been an increase in attention to robust electric power system control [28, 29], and on the other hand to the demand side management for effective electricity supply [30, 31].

Research efforts aimed at optimal implementation of renewable and alternative energy sources in electric power systems [32-34], including in connection with the future spread of electric vehicles [35, 36]. Progress in the use of energy storage systems becomes important for effective management to compensate volatile electricity production from stochastic renewable sources [37, 38]. At the end of the review period, the development and operating becomes an unexpectedly popular topic [39]. The general trend of the second period is also that researchers are interested in the appropriate approaches and tools for modeling and optimizing transforming energy systems [40, 41].

V. Conclusions

This work presents a scientometric review of energy systems research for the last two decades 2001-2021 through an exhaustive analysis of research literature retrieved from the Scopus database. In opposite to the other bibliometric studies in the energy field, this analysis mainly focuses on the topic structures and its and temporal evolution. The document co-citation network was built on the basis of more than 100,000 publications. In addition, the top 50 publications with strong citation bursts were analyzed. Thus, the general topics hotspots and development trends in the research of energy systems were evaluated and visualized.

This study has several limitations. First, it should be noted that the semantic meaning of the basic terms of the study concerns mainly electric power systems, but not energy systems in general. In the study, energy systems related to heat supply and different types of perspective fuel supply (natural gas, hydrogen, methanol, etc.) were poorly considered.

Another limitation is the nonuniform temporal resolution at the construction of the document co-citation network. It is difficult to identify representative clusters in earlier periods, as there was increased publication activity and abundant citations from the middle of the 2010s. This drawback can be overcome in future research through the use of a dynamic thresholding g-index value.

The study represents the dynamics in the most common topics in the knowledge domain, but deeper semantic structures and their interrelations remained outside of the consideration. The quantification and classification of the multidisciplinary and complex field of energy systems is not simple. Future work implies the use of a predesigned hierarchical ontology to overcome existing gaps and to build an adaptive semantic model of developing the knowledge domain of energy systems.

The preliminary results of the study were presented and discussed at the conference "Information and Mathematical Technologies in Science and Management", June 29 - July 8, 2021, Irkutsk, Russia.

Acknowledgments

The research is funded by the Russian Foundation for Basic Research (project No. 20-07-00994).

References

[1] Araújo, K. (2014). The emerging field of energy transitions: Progress, challenges, and opportunities. Energy Research and Social Science, 1, pp. 112–121. https://doi.org/10.1016/j.erss.2014.03.002

[2] Dovì, V. G., Friedler, F., Huisingh, D., & Klemeš, J. J. (2009). Cleaner energy for sustainable future. Journal of Cleaner Production, 17(10), pp. 889–895. https://doi.org/10.1016/j.jclepro.2009.02.001

[3] Bale, C. S. E., Varga, L., Foxon, T. J. (2015). Energy and complexity: New ways forward. Applied Energy, 138, pp. 150–159. https://doi.org/10.1016/j.apenergy.2014.10.057

[4] Voropai, N.I., Stennikov, V.A., Senderov, S.M. (2020). Infrastructural Cyber-Physical Energy Systems: Transformations, Challenges, Future Appearance. Energy Systems Research. 3(3), pp. 18-29. https://doi.org/10.38028/esr.2020.03.0003

[5] Balakrishnan, D., Haney, A. B., & Meuer, J. (2016). What a MES(s)! A bibliometric analysis of the evolution of research on multi-energy systems. Electrical Engineering, 98(4), pp. 369–374. https://doi.org/10.1007/s00202-016-0427-9

[6] Dominković, D. F., Weinand, J. M., Scheller, F., D'Andrea, M., & McKenna, R. (2022). Reviewing two decades of energy system analysis with bibliometrics. Renewable and Sustainable Energy Reviews, 153. https://doi.org/10.1016/j.rser.2021.111749

[7] Celiktas, M. S., Sevgili, T., Kocar, G. (2009). A snapshot of renewable energy research in Turkey. Renewable Energy, 34 (6), pp. 1479–1486. https://doi.org/10.1016/j.renene.2008.10.021

[8] Montoya, F. G., Montoya, M. G., Gómez, J., Manzano-Agugliaro, F., Alameda-Hernández, E. (2014). The research on energy in Spain: A scientometric approach. *Renewable and Sustainable Energy Reviews*, 29, pp. 173–183. https://doi.org/10.1016/j.rser.2013.08.094

[9] Mikheev, A.V. (2020) Knowledge Mapping of Energy Systems Research in 1970-2020. Energy

Systems Research. 3(3). pp. 54-61. https://doi.org/10.38028/esr.2020.03.0007

[10] Chen, C. (2006). CiteSpace II: Detecting and Visualizing Emerging Trends and Transient Patterns in Scientific Literature. *Journal of the American Society for Information Science and Technology*, 57(3) (February 1), pp. 359–377. https://doi.org/10.1002/asi

[11] Hou, J., Yang, X., Chen, C. (2018). Emerging trends and new developments in information science: a document co-citation analysis (2009–2016). *Scientometrics*, 115 (2), pp. 869–892. https://doi.org/10.1007/s11192-018-2695-9

[12] Kim, M. C., Zhu, Y., Chen, C. (2016). How are they different? A quantitative domain comparison of information visualization and data visualization (2000–2014). *Scientometrics*, 107(1), pp. 123–165. https://doi.org/10.1007/s11192-015-1830-0

[13] Chen, C., Song, M. (2019). Visualizing a field of research: A methodology of systematic scientometric reviews. PLoS ONE, 14(10) https://doi.org/10.1371/journal.pone.0223994

[14] Chen, C. (2014). CiteSpace Manual. https://doi.org/10.1007/s11192-015-1576-8

[15] Liu, C., Gui, Q. (2016). Mapping intellectual structures and dynamics of transport geography research: a scientometric overview from 1982 to 2014. *Scientometrics*, 109 (1), pp. 159–184. https://doi.org/10.1007/s11192-016-2045-8

[16] Chen, C., Ibekwe-SanJuan, F., Hou, J. (2010). The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis. *Journal of the American Society for Information Science and Technology*, 61 (7), pp. 1386–1409. https://doi.org/10.1002/asi.21309

[17] Kundur, P. (1994) Power System Stability and Control, McGraw- Hill, New York, 1200 p.

[18] P. W. Sauer and M. A. Pai, (1998) Power System Dynamics and Stability, Prentice-Hall, Inc., New Jersey, USA,

[19] Kundur, P., Paserba, J., Ajjarapu, V., et al. (2004). Definition and classification of power system stability. IEEE Transactions on Power Systems, 19(3), pp. 1387-1401. https://doi.org/10.1109/TPWRS.2004.825981

[20] Ackermann, T. (2005) Wind Power in Power Systems. John Wiley and Sons, Ltd., Hoboken. 742 p.

[21] Lund, H. (2004) Large-scale integration of wind power into different energy systems. *Energy*, 30(13), pp. 2402-2412. https://doi.org/10.1016/j.energy.2004.11.001

[22] Carrasco, J. M., Franquelo, L. G., Bialasiewicz, J. T., et al. (2006). Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on Industrial Electronics*, 53(4), pp. 1002-1016. https://doi.org/10.1109/TIE.2006.878356

[23] Lund, H. (2007). Renewable energy strategies for sustainable development. *Energy*, 32(6), pp. 912-919. https://doi.org/10.1016/j.energy.2006.10.017

[24] Lund, H., & Kempton, W. (2008). Integration of renewable energy into the transport and electricity sectors through V2G. *Energy Policy*, 36(9), pp. 3578-3587. https://doi.org/10.1016/j.enpol.2008.06.007

[25] Blaabjerg, F., Teodorescu, R., Liserre, M., & Timbus, A. V. (2006). Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics*, 53(5), 1398-1409. https://doi.org/10.1109/TIE.2006.881997

[26] Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., & D'haeseleer, W. (2005). Distributed generation: Definition, benefits and issues. *Energy Policy*, 33(6), pp. 787-798. https://doi.org/10.1016/j.enpol.2003.10.004

[27] Chicco, G., & Mancarella, P. (2009). Distributed multi-generation: A comprehensive view. Renewable and Sustainable Energy Reviews, 13(3), pp. 535-551. https://doi.org/10.1016/j.rser.2007.11.014

[28] Pal B., Chaudhuri B. (2005) “Robust Control in Power Systems,” Springer, New York, 190 p. https://doi.org/10.1007/b136490

[29] Bevrani H. (2009) “Robust Power System Frequency Control,” Springer, New York, 226 p. https://doi.org/10.1007/978-0-387-84878-5

[30] Strbac G. (2008) Demand side management: Benefits and challenges, *Energy Policy*,36(12), pp. 4419-4426 https://doi.org/10.1016/j.enpol.2008.09.030

[31] P. Palensky (2011) Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads, *IEEE Transactions on Industrial Informatics*, 7(3), pp. 381-388, https://doi.org/10.1109/TII.2011.2158841

[32] A. Tuohy, P. Meibom, E. Denny, M. O'Malley, (2009) Unit Commitment for Systems With Significant Wind Penetration, *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 592-601, https://doi.org/10.1109/TPWRS.2009.2016470

[33] Zhou, W., Lou, C., Li, Z., Lu, L., & Yang, H. (2010) Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. *Applied Energy*, 87(2), 380–389. https://doi.org/10.1016/J.APENERGY.2009.08.012

[34] J. M. Morales, A. J. Conejo and J. Perez-Ruiz (2009) Economic Valuation of Reserves in Power Systems with High Penetration of Wind Power, *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 900-910, https://doi.org/10.1109/TPWRS.2009.2016598

[35] Kempton, W., & Tomić, J. (2005). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *Journal of Power Sources*, 144(1), 280–294. https://doi.org/10.1016/J.JPOWSOUR.2004.12.022

[36] K. Clement-Nyns, E. Haesen and J. Driesen, (2010) The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid, *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 371-380, https://doi.org/10.1109/TPWRS.2009.2036481

[37] Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, 19(3), 291–312. https://doi.org/10.1016/J.PNSC.2008.07.014

[38] Beaudin, M., Zareipour, H., Schellenberglabe, A., & Rosehart, W. (2010). Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy for Sustainable Development, 14(4), 302–314. https://doi.org/10.1016/J.ESD.2010.09.007

[39] Hirsch, Adam & Parag, Yael & Guerrero, Josep, (2018). Microgrids: A review of technologies, key drivers, and outstanding issues, *Renewable and Sustainable Energy Reviews*, vol. 90(C), pages 402-411. https://doi.org/10.1016/j.rser.2018.03.040

[40] Connolly, D., Lund, H., Mathiesen, B. v., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy, 87(4), pp. 1059–1082. https://doi.org/10.1016/J.APENERGY.2009.09.026

[41] Rashedi, E., Nezamabadi-pour, H., & Saryazdi, S. (2009). GSA: A Gravitational Search Algorithm. Information Sciences, 179(13), pp. 2232–2248. https://doi.org/10.1016/J.INS.2009.03.004

Alexey V. Mikheev graduated from the Faculty of Mathematics of the Irkutsk State University. He has PhD in energy and engineering. Main research fields are mathematical modeling of energy systems and power units, energy technology forecasting, scientometric and bibliometric analysis, image processing, optical measurements, flow visualization, software development.