Multiagent Resource Planning System for Utility Provision

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Abstract: The intensive economic and social development of smart cities faces the constraints of stable utility provision. This paper presents a multiagent client-centric smart grid management system for integrated gas, heat and electricity networks. The system is based on the new approach of agent's negotiation implementing the strategies of straight and reverse recursion planning. It can be used as part of the Smart grid and Micro grid concepts to reduce the price for consumers and decrease the negative impact of peak loads for the suppliers. This approach corresponds to the fundamental principles of modern complexity theory, which uses the fundamental principles of self-organization and evolution inherent in the natural world.

1 INTRODUCTION

The intensive economic and social development of smart cities faces the constraints of stable utility provision. The constantly increasing demand for resources reveals several limitations related to the high cost of production, ecology, the level of energy losses in the network, and outdated organization methods. One more limitation is the infrastructure of a residential area as a conglomerate of complex technical systems embedded in dense urban or industrial development landscapes. Every city has its characteristics and is essentially unique. Some are characterized by cogeneration of electricity and heat, while others use combined district heating schemes with private boilers.

These factors show great potential for adapting the smart grid (SG) methodology for electricity, heat, and gas supply systems.

This paper presents a multiagent client-centric smart grid management system for integrated gas, heat and electricity networks.

The article's scientific novelty lies behind the agents' newly presented logic, the negotiation protocol, where users are part of the decision-making process, and the software approach of agents and ontologies combination. The practical value is the implementation of the complex solution based on the SG concept that can optimize supply-demand model of all three types of utilities (gas, heat, electricity) in one software taking into account of specific infrastructure constraints. Experimental results have shown that system implementation can reduce the price for the end-user.

2 STATE OF THE ART

The term "Smart grid" is still quite vague and for this research the smart grid is defined through basic features, among them (Report Australian energy operator, 2020):

- optimal resources load to increase efficiency, reduce losses and devices failure;
- active role of consumers in the network;
- the ability to resist new, unplanned events;
- synchronous operation of all network elements.

Multiagent Systems (MAS) now are SG enabling technology because they can possess all mentioned features, they can give a distributed software framework and bring intelligence to the grid (Brena, Handlin, Angulo, 2015). Agents are widely used as

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the instrument of negotiating on the low sensor level. In (Nguyen and Flueck, 2015), the idea of an agent-based distributed power flow solver for unbalanced radial distribution systems based on MAS is presented. Since the 2000's researchers have tried to use intelligent agents because of three main key features: autonomy, local view, and decentralization. However, most methods use agents to model lines, switching devices, voltage regulators, transformers, distributed energy storage systems, and batteries (for example to solve the backward/forward sweep technique problem to solve the power flow iteratively) (Boudaoud, Labiod, Boutaba, Guessoum, 2000).

MAS is widely used in Smart Homes (Li, Logenthiran, Woo, 2015) to optimize the energy consumption on a local house/flat level. Agents help to plan the optimal solution of energy consumption, but they do not provide a real-time response to all unpredictable events. They are used to achieve high comfort level, energy efficiency, and energy price through negotiation between devices.

In (Omarov, Altayeva, 2018) the methodology of MAS is used in intelligent control systems that covers all the monitored zones of a building and, if necessary, provides the greatest possible overall comfort in the building while reducing the required electric power.

A more comprehensive simulation approach that accounts for the MAS-related protocols as described in the FIPA specification is presented in (Le, Bui, Ngo, 2018). It shows promising results for system evaluation under various settings and design trade-offs.

Agents communication is performed to transfer neighbouring information between subsystems. It is shown the possibility of parallel work in different parts of the distributed network (Shum, 2106).

Agent approach is fundamentally based on negotiation to find the optimal (or close to the optimal solution). For this purpose, Combinatorial Auctions can also be used. The proposed combinatorial auctions algorithms showed an advantage over a more rigid scheduling algorithm (Brena, Handlin, Angulo, 2015). This approach can predict and plan but not manage the system in real-time.

One of the main advantages of MAS is the ability to work in decentralized systems for electricity provision (Svítek, Skobelev, Kozhevnikov 2020). It Is Used Extensively in Research Projects (Morte, 2016) To Develop Distributed Control Systems Comprised of a Network of Communicating Units. The Task To Be Solved Is The Issue of Complexity That Scales Up Exponentially, Limiting The Development of Smart Grid Technologies.

Decentralization of The Network With The Help of Multiagent Systems for Electric Vehicles Infrastructure Is Described in (Jordán, Palanca, Del Val, Julian, Botti, 2018). Agents Collect, Evaluate and Manage Data from Elements To Create an Optimal Cooperation Algorithm.

in (Loni, Parand, 2017) The Game Theory for The Smart Grid Topic Is Implemented. The Game Theory Models The Behaviour of Independent and Rational Agents To Maximize The Profit. Authors Survey Several Game Theory-based Applications, Incredibly Cooperative Game Theory To Solve Relevant Problems in Micro Grids.

a Tremendous Analysis of The MAS Application in SG Is Done in (Mahela Et Al., 2020). Comprehensive Overview of Multi-Agent Systems for Controlling Smart Grids. CSEE Journal of Power and Energy Systems.). Completed The Review of General Concepts of Smart Grids and MAS, Technologies and Standards, Intelligent Agents in SG and Commercial Projects The Authors See The Future of MAS in Coordinated Control Replacing SCADA Systems.

based on The Topic Domain Review, We Can Define The Trend for MAS Coordinated Control of The SG and Lack Decision-Making Solutions That Can Be Applied for Limited Tasks With Severe Constraints. on The Other Hand, It Is Clear That The Multiagent Approach Can Be Successfully Used for Distributed Problem Solving in Decentralized SG Architectures.

in Our Project, We Extend The SG Concept from Electricity To All Types of Resources (Electricity, Gas, Heat). for Citizens It Is a Part of Utility Provision of The Smart City Concept in General (Přibyl, Horák, 2015).

The State-of-The-Art Review Highlights The Main Advantages of MAS. Multiagent Resource Planning System for Utility Provision Can Plan and Optimize Utility Provision as a Multi-Criteria Task, Moving from Determining The Optimum Under given Constraints (Reliability, Quality, Environmental Friendliness) To Finding The Optimal Level Ratio of These Properties.

3 MULTIAGENT SYSTEM FOR UTILITY PROVISION

3.1 System Functions

Base on the state of the art and market analysis the consumer-friendly MAS with the following functions was developed. Main system functions:

- development of a model and plan of resource production and consumption processes taking into account the current situation at the network objects;
- real time optimization of production/ consumption plan of resources;
- simulation of production/consumption process for three types of resources in any predefined scale;
- coordination of decision-making process with end-users through two-way interaction;
- conducting simultaneous analysis of multiple planning options with appropriate allocation of resources for optimization purposes.

3.2 Types and Characteristics of System Objects

The main objects in the system are: suppliers (produce one or several types of resources), consumers (consume one or several types of resources), network elements (transmit the resource from supplier to consumer).

3.2.1 Suppliers

Focusing on statistical and forecast demand data suppliers make plans for resource production. Produce resources of one or several types:

- Gas. The supplier represents one of the state gas supply system branches - a gas distribution station. In the model context, the gas supplier's production capacity is equal to its throughput capacity.
- Heat. Can be presented as city level suppliers (thermal power station) acting through the public heat supply network, or local suppliers. The thermal power station can work as cogeneration plant and can operate in two modes: *thermal* - heat load is the priority, *electric* - electric load is the priority.
- Electricity. Electricity can be supplied by cogeneration plants, hydroelectric power plants, or local generators.

3.2.2 Consumers

Consume resources requested from suppliers, and delivered through networks corresponding to the three types of resources. The sum of all requests forms a general graph of resource consumption, affecting the volume of the resource production.

Consumers can be divided to industrial (factories, plants, etc.), offices, and household users. The main difference between them in volumes of resource consumption, range of planning horizon, and discreteness of consumption plans.

The supplier of resources can also be a consumer.

3.2.3 Storages

Can be both consumer and supplier. Storages can accumulate a certain amount of resources - gas or electricity. Storages are characterized by the capacity and the ability to return the accumulated resource.

3.2.4 Transformers

Resource transformers can change the types of the transmitted resource (for example, change gas to electricity).

3.3 Types and Characteristics of Network Channels

There are three types of channels provided by the resource-supply network - gas, electric and heat.

3.3.1 Gas Supply Channel

Presented in the system as trunk and city pipelines. The trunk pipeline delivers the gas to distribution stations where the pressure is lowered to the required level.

3.3.2 Heat Supply Channel

Delivers heat, in this project (as usually in real cities), this channel is not reconfigurable part of the infrastructure network.

3.3.3 Electricity Supply Channel

The structure (way of distribution) of the network can be changed to optimize the electrical model of the network.

3.4 System Ontology

Integrated resource supply network pursues the goal of transporting gas, electric, and heat resources from producers to consumers. Visually such a network can be represented as a connected graph (Figure 1). The paths in this case can be called channels and divided into three types (gas, electricity, heat channels). Objects are divided into four types - supplier, consumer, storage, transformer. For every element we can also define subspecies, based on the relationship of these objects to one or another type of resources.

In the developed system, the description of the main elements was done in the network ontology editor. It allows creating the predefined ontology classes of objects, to assemble the network, start planning, and simulate the process of resource distribution in real-time.

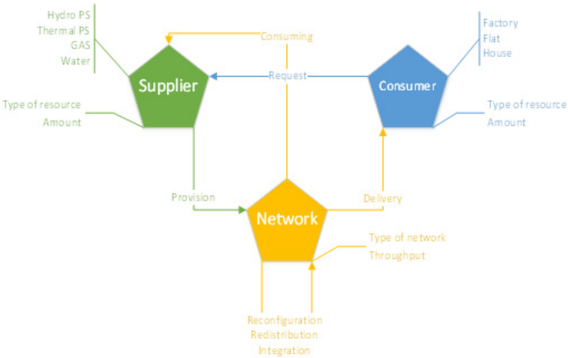

Figure 1: Ontology of a problem domain.

Network ontology editor allows the creation of the predefined and new classes of main and auxiliary objects (substations, solar panels) to assemble the network. New object classes can be included in the network by extending the ontology and adding classes of appropriate agents.

3.5 Description of Planning Algorithms

3.5.1 MAS Approach

In this project MAS implies matching of every object with its own software agent (SA). SA description includes the characteristics of the simulated object that are stored and can be changed in the ontologically descriptive knowledge base (network ontology editor). Dynamically generated solutions are achieved in the process of communication of agents that is carried out by transmitting the predefined types of messages.

The optimization problem of the model is solved based on the market approach. It can be described as:

- expression of all optimization parameters is developed through universal cost characteristics (internal virtual currency);
- the rules of agents' behaviour aimed at increasing the local profit of every agent by reducing the costs in the virtual currency, which leads to dynamic improvement of the network parameters;
- automatically finding the optimal dynamic equilibrium of the multiagent system by exchanging virtual currency;
- applying internal agent penalty and bonus functions to control the dynamics of the network automatically;
- use of scalar convolution on parameters of optimization of the network agents' state;
- use a component-by-component variation of optimization parameters of the multiagent system in order to align the indicators.

The proposed multiagent technology based on the market approach provides universal and dynamic optimization for software-configurable networks.

3.5.2 Type of Agents

In the developed system, the planning and resource allocation task is solved by agent's negotiation and successive approximations from essential, simple, fast solutions to a more complex and efficient one according to the available time. Software agents optimize their target parameters, identify conflicts, negotiate, make concessions and achieve a solution in the interests of the whole system.

The main types of agents in the developed system are:

- Order agent (represents the consumers and requests for specific resource. Every consumer can generate various number of orders for different resources. Every request creates a separate agent).
- Scene agent (system agent. Responsible for agent’s management process).
- Resource Agent (represents the suppliers and amount of resources of various type can be provided. Every supplier creates one agent for every type of available resource).

3.5.3 Initial Parameters and General Planning Description

Every consumer has its own resource consumption plan, visually represented (Fig. 2) as a two-dimensional graph with the axes of time and volume (GCal, m3 and kW), respectively, with discretization by hours/days. Users set consumption plans with a monthly horizon based on the average rate typical for this area.

Users set up, edit, and approve the plans privately. The system summarizes requests, creating three aggregated plans for each type of resource in general.

The system then identifies peaks in these aggregate schedules and starts the negotiation process. It looks for the consumers who have invested the most significant contribution to the plan and then starts to trade to decrease request and ensure the sufficiency and stability of the whole plan.

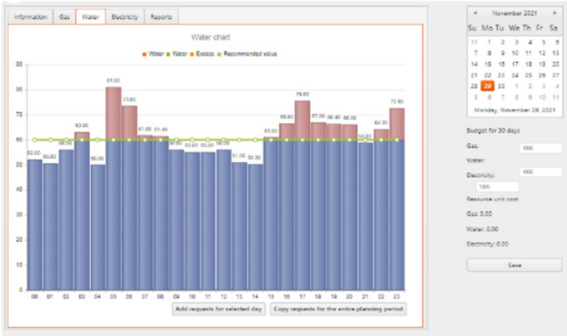

Figure 2: Consumption plan.

After negotiating, the system approves a resource consumption plan that satisfies all users. There is now a penalty if consumers use fewer/more resources than requested and planned as a preventive measure implemented to oblige consumers to comply with the established plan.

There are three main phases of planning in the system: initial flat planning, proactive orders and resources phases.

3.5.4 The Initial Flat Planning Phase

The initial planning phase is shown on Fig.3.

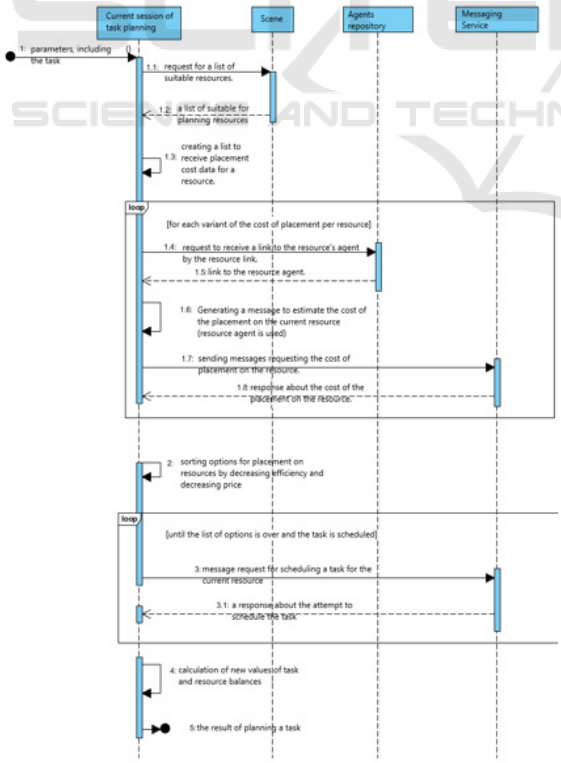

Figure 3: Flat planning diagram.

The flat planning phases runs as follows:

a) The Order agent receives a scheduling request message from the Scene agent.
b) The Order agent determines the list of potentially suitable resource suppliers for planning this order.
c) A request to the Scene is generated to obtain a list of resource suppliers capable of performing the order. Capability is based on the type of energy resource, network channels, and links between suppliers and consumers.
d) A list of resource suppliers suitable for the order is returned.
e) The Order agent subscribes through the message service to receive information from the Resource agents about the price needed to perform the request.
f) Through the agent repository, the Order agent receives the list of Resource agents (received in step C) and forms a list of potential further request messages for the price of placement of the request.
g) Through the message service, the Order agent sends to every Supply agent a request message for the price of order placement for a certain time interval. The message specifies the size of the request, the time interval from t1 (now) to t2 (planning horizon). On this step only open and available slots are taken into account.
h) The Order agent gets responses from the Resource agents to the request-message about the price and time. The result is a set of all possible placements on suitable resources. The answer message can provide several variants of one order placement because it can fit several variants in the planning interval due to the different prices at all possible t1-t2 time intervals.
i) The Order agent sorts the possible variants and keeps those where the price is less than the initial amount of virtual money left.
j) On every received interval a set of possible variants of placement is determined to calculate the value of the target function. Two values sort the obtained list: decreasing of the target function and the price of resource placement.
k) The list of sorted options for order placement is used by the Order agent. It sends the planning request message and tries to schedule the order on the resource - first in the list. The message contains the order ID, the desired time, the price in virtual currency that the order can pay for the placement.

l) Upon the receiving of a message of successful order placement, an amount equal to the difference of the initial amount of money and the cost of scheduling for the selected resource is credited to the virtual currency account.

m) When the order is successfully scheduled, the Resource agent credits the amount received from the system to his account.

n) In case of the order is not scheduled the next possible resource from the list receives a request for order placement. The planning can be unsuccessful because of the increase in the resource rate at the requested interval, or there is another order on this time interval, or the starting time of the order left.

o) In case of the order does not find the appropriate resource (from the list) and allocation place, it stays unplanned.

3.5.5 Phase of Proactive Analysis and Redistribution of Orders

The system has the option of proactive agent's behaviour and order analysis (agents proactively look for better options to place the order after the completed first round of planning). In this case, the negotiation process runs as follows:

a) The Scene agent selects all the orders that are planned but not yet executed at the moment.

b) For each selected order, the current value of its target function is calculated.

c) The list of selected orders is sorted by the ascending value of the target function.

d) The scene agent sends request messages for the moving price for a certain number of the most dissatisfied with its placement orders (at the beginning of the list).

e) The Order agent that receives the message requests a Scene agent the list of resource suppliers capable of performing the required list of orders and sorts it according to their desirability.

f) For each resource from the received list (including the current resource supplier where the order is currently planned), a sample of possible placement points is made, taking into account the order size, performance, minimum time step (ξ) and planning horizon (T). In Fig. 4, sample points are indicated with round dots.

Figure 4: Sample point for order placement.

g) For all selected sample points, the Resource agent calculates and sends the Scene agent the price for placing the order.

h) In case this time interval is already occupied with scheduled orders, the system selects the orders that interfere.

i) The Scene agent sends the request to the preselected orders for the possibility to move for the specified time left or right (Fig. 5).

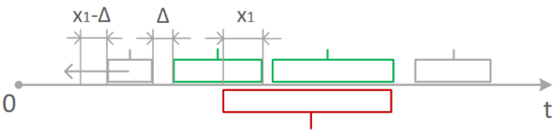

Figure 5: Scheduled orders (green) interfere with the new order (red).

j) The preselected Order agents receive the shift request and start the process of negotiation with the Resource agent.

k) The preselected Order agents send the request to the corresponding Resource agent to find out the price of placing the order on another time interval.

l) If moving to the new time interval influences other scheduled orders, their agents also request to move. This request contains the pre-calculated value and direction of the shift. Recursive descent continues until the next order to be shifted can move to the new position unhindered, or up to the counter limiting the recursion depth (set in the settings).

m) In the reverse recursion, the affected agents send response messages containing information about all required moves and its total cost (Fig. 6).

n) As a result, each placement point has its cost. The cost is calculated as the price for the resource and the price for moving the affected orders.

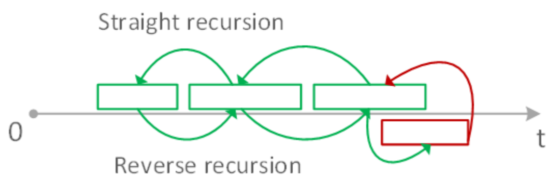

Figure 6: Straight and reverse recursion.

o) From the whole set of possible placement points, the system excludes those with the price exceeding the order's available virtual money. Next, the system excludes allocation options that do not improve the target function's value if approved.

p) The remaining set of allocation points is sorted in descending order of their efficiency, expressed in improving the value of the system's target function. In case of equality, the points with less value are preferred.

q) In the response message (for the Scene agent), the Request agent specifies the full cost and the array of required shifts necessary to move the request to the sorted set's first (best) point.

r) Changes are approved and performed if the total cost specified in the message is less than the sum of the virtual money of the Order agent and the virtual money returned by resources for unscheduling the order.

s) Prior to reallocation, the system checks the relevance of the schedule and it is subsequently blocked. If changes are detected in the schedule, the reallocation is not performed.

t) As the next step the system tries to remove all orders of the schedule affected by the reallocation. If unsuccessful, the reallocation is not performed, and the schedule returns to its original state.

Elements removed on the previous step are moved to new positions.

3.5.6 Phase of Proactive Resource Analysis and Load Redistribution

The system has the option of proactive resource analysis (agents proactively look for better resource load options after the completed first round of planning). In this case the negotiation process runs as follow:

a) The order whose de-scheduling leads to the highest efficiency of the system is selected.

b) The order is removed from the schedule (in this case the schedule of proactive resource is blocked from editing by other processes):

- The virtual money paid for placement in the schedule is returned.
- The data about the old placement on the resource's schedule is deleted.
- The Order agent send the new request for planning.
- If the process is unsuccessful at any stage - the schedule and orders are returned to the initial state (before the reallocation attempt).

Process of proactive analysis and redistribution of orders and resources is shown on Fig.7.

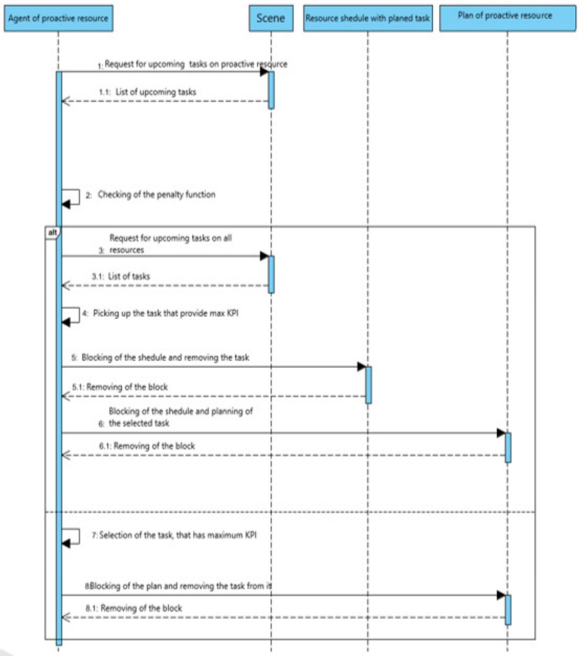

Figure 7: Proactive agents diagram.

3.5.7 Penalty Function

The penalty function (Fig. 8) is used to vary through the special admin. user interface the agent's objective function. It makes possible to increase or decrease the level of agent's mobility.

Depending on the value of the current KPI, the components of the agent's objective function have different characteristics with a maximum at the optimum value.

On the interval (0, 0.2), when resource proactivity is activated, step 6 is executed (Fig. 7), on the interval (0.2, 0.6) step 8 is executed, and on the interval (0.6, 1) step 7 is executed.

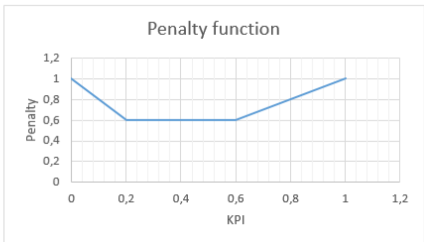

Figure 8: The penalty function.

The penalty function can be adjusted to the specific task or certain logic of the model. In the developed system and performed test cases the penalty function is connected with the maximum load of the suppliers. As the KPI equal the load, the minimum penalty equal to the optimal modes of equipment.

3.6 Developing Scenarios and Performing Tests

3.6.1 Initial Problem Statement for Test Scenario Development

For the test scenario the small village had been chosen. The network and objects configuration of the village as a set of suppliers and consumers of resources is presented in Figure 9 (five suppliers of three different types of resources).

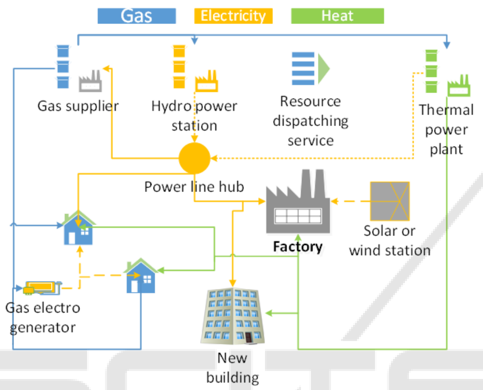

Figure 9: Configuration of the test network.

The parameters of the suppliers are presented in Table 1. Every supplier can change and decrease the amount of produced resources.

Table 1: Parameters of the suppliers.

Supplier	Resource type	Max. production
Hydroelectric power plant	Electricity	150/225 KwH
Gas supplier	Gas	60000 m3/Month
Thermal power plant	Electricity/Heat	170 KwH
Thermal power plant	Electricity/Heat	170 KwH /1800 m3/month
Wind power station	Electricity	30 KwH

It is assumed that every object has access to the dispatching service to change the rate of consumption of resources. All objects have sensors to count the current level of consumption of resources.

The simulation starts after formalizing the network of consumers and suppliers of resources, defining their relationships and parameters. During the modelling process it is possible to enter additional events (new additional demand) that influence and refine consumption forecasts. Other types of events (new consumer or supplier, issues with the network, revise of the price) may also change the general forecasts and the prices and plan of the delivery can be dynamically recalculated.

In this context, the developed system can show how intelligent planning and the forecast availability can reduce the production costs for suppliers and reduce the price for the users.

3.6.2 Performing Tests

To prove the concept, the test scenarios were conducted. In the modelled scene a village with 15 private houses with consumption rates is slightly deviating from the average normative values. The degree and vector of deviation were set by the system for each object individually in an automatic random way, taking into account the given constraints. Additionally, to the basic scenario, a gas-electric power generator can be used by private homes. The factory, with predefined schedule of consumption, with a given slight fluctuation. The factory has its own source of energy as a set of solar panels. Fluctuation in the volume of electricity consumption by the factory depends on the solar panels capacity.

Thermal power plant loaded to 30% of resource capacity The load on the turbines of the hydroelectric power plant is 80%.

All presented consumers are connected to all types of resources. All suppliers are consumers of all resources except those that they produce themselves. Figure 9 shows a simplified diagram of the network topology designed for the experiment.

Having the initial data, the system builds the consumption plan of all three resources defining the peak hours of electricity. As the next step the system in the proactive phase rebuild a plan reducing the peak hour’s consumption.

After the basic scenario, new external conditions of increased demand for electricity from the factory were implemented. This case leads to the additional production of electricity by the thermal power plant, what leads to the additional production of heat for the lower price for the user in public heat supply network.

The results of the planning in Figure 10 show the changes in the price of the utilities for users before and after implementation of the system.

It is shown, that adaptive rescheduling in the network of objects connected in one smart grid and multiagent resource planning system for utility provision in cooperation with solar panels installation can reduce the price of the electricity more than 2 times.

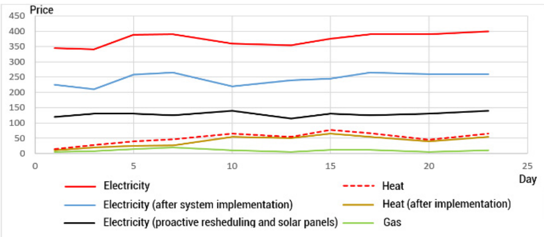

Figure 10: Results of the experiment.

4 CONCLUSIONS

Multiagent resource planning system for utility provision is designed to: improve the efficiency of utility model by applying real-time planning. It helps to optimize the production-consumption model, make short-term and long-term planning for optimal operation modes and effectively balance the market in local micro grids and more complex smart grids. The multiagent system implements a variety of methods for the distributed solution of complex problems.

The solution is sought based on the model of interaction of software agents, which negotiate in achieving the goal and seek consensus, for which conflicts are sought and resolved by mutual concessions, to achieve the most rational solution to the common problem.

The system optimizes the processes of production and consumption of three types of resources in one model and present the schema for gas, heat, and electricity supply systems integrity. It shows an individual approach for every order and resource through taking into account the various strategies and criteria, preferences and constraints of all players.

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