Holonic approach in control of the future district heating and cooling systems

Lubomir Vasek and Viliam Dolinay

***Abstract*—** This paper reflects on the modern concepts of production, supply and consumption of heat and cool in urban agglomeration in so called District heating and cooling (DHC) systems. Generally, a future concept for these systems expects also use of smaller decentralized sources, which utilize residual heat and renewable energy. To control such a system it seems the most appropriate to use some of the concepts of distributed control. In our case it will be holonic concept, in processes inside the DHC. The basic ideas of Holonic control are shown and steps necessary to incorporate it inside the DHC are described. These steps are based on analysis of the DHC processes and aimed at the formulation of the suitable holarchy for it. The individual holons and its function will be shown as well as services that provide their mutual cooperation. The example at the end of this article will show implementation for one of the system parts – CHP source.

***Keywords*—** Cogeneration, district heating, distributed control systems, heat distribution and consumption, holarchy, holon, Smart Thermal grid.

I. Introduction

The key objective in the field of energy efficiency is to lower consumption of primary energy as much as economic performance allows [1]. This is also the objective of most countries who want to behave ecologically. To reduce primary energy usually means:

- Modernize and improve the efficiency of technological equipment for heat production (improving the combustion process, development of modern boilers, etc.)
- Use broader engagement of energy from renewable energy sources (RES), which is not be ranked among primary energy.
- Use of secondary heat sources - waste heat from industrial processes, low-potential sources and municipal waste incineration.
- Insulation - reduce losses in the distribution network and heated objects.
- Heat management optimization.

Addressing heat management optimization together with wider use of RES and waste heat is included in the Smart Thermal Grid (STG) concept [9]. In fulfilling this concept is also trying to contribute our proposal distributed district heating control system, which should be built on the idea of holonic structure. The primary idea is however distributed concept itself, which may not necessarily be called holonic, we can understood it as a system of cooperating agents with which is usually a general reader more familiar.

This article will try to show how such a system should be designed - how to divide tasks for individual Holons, how to build a holarchy and what services must be implemented to ensure the optimal performance of the entire system. Because control, or more appropriately management of STG is a huge field and each location can also offer other possibilities, the article will not try to cover the entire field but focus on one sub-area which is CHP sources.

II. District Heating and Cooling

Classical district energy systems produce steam, hot water or chilled water at a central plant [10]. The steam, hot water or chilled water is then piped underground to individual buildings for space heating, domestic hot water heating and air conditioning. As a result, individual buildings served by a district energy system don't need their own boilers or furnaces, chillers or air conditioners. The district energy system does that work for them, providing valuable benefits including:

- Improved energy efficiency
- Enhanced environmental protection
- Fuel flexibility
- Ease of operation and maintenance
- Reliability
- Comfort and convenience for customers
- Decreased life-cycle costs
- Decreased building capital costs
- Improved architectural design flexibility

In addition, district energy systems can use the "reject heat" that results from burning fuel to produce electricity at a power plant, dramatically increasing the overall efficiency with which

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useful energy is extracted from the fuel.

The reject heat can be used to spin turbines and generate electricity. This arrangement, called "combined heat and power" (CHP). A CHP system may have double the fuel efficiency of an electric generation plant and can also lower the emissions typically associated with conventional fossil-fuel powered electrical production. The less energy used, the less sulfur dioxide and carbon dioxide and other emissions are expelled into the environment [2].

Comparison of CHP and standard power plant energy efficiency presented by International District Energy Association is shown in fig. 1.

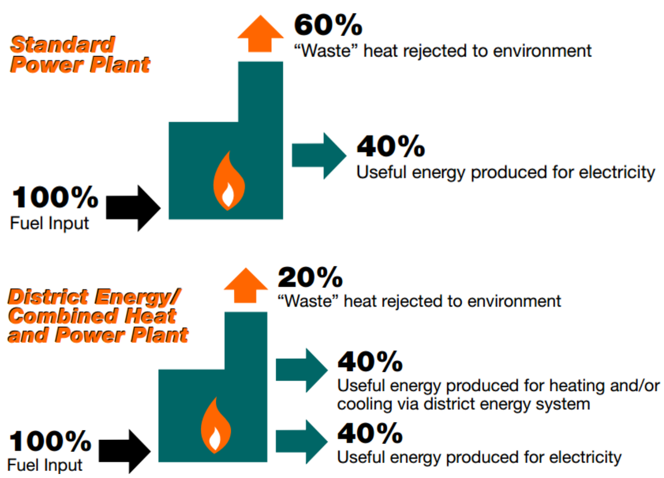

Fig. 1. Energy-efficiency comparisons [2]

A. Heating and cooling strategy for Europe

Every community, as well as EU must plan. In the energy sector pays more than elsewhere, the strategy must be long-term. New technologies, energy systems, heat sources cannot be put into practice in a few years, the decades are usually needed.

EU presents its concept until 2050, with the individual - successive milestones. More details can be found here: https://ec.europa.eu/energy/en/ topics/energy-strategy.

The strategy can be generally concluded in the following four points [14]:

- Energy Efficiency: heat savings are a key component in the decarbonisation of the EU energy system. The total heat demand in Europe should be reduced by approximately 30-50%.
- District Heating: There is currently more heat being wasted in Europe than is required to heat all of the buildings. District heating can capture this excess heat and move it into the buildings. District heating should be increased from today's level of ~10% up to ~50% in 2050.
- Individual Heat Pumps: in rural areas, individual ground and air-sourced heat pumps should replace existing oil boilers. Heat pumps connect cheap renewable electricity production (such as wind and solar) with efficient renewable heat production (due to their COP).
- Energy System: heat savings, district heating, and individual heat pumps are key components in a future low-carbon EU energy system. They are fundamental to the technical and economic viability of the Smart Energy System.

Energy efficiency which is associated with reducing of carbon dioxide was already mentioned at the beginning of this chapter, in the context of the importance of combined heat and power production. This CHP technology is implemented in most countries and for example, in the Czech Republic, the power plant without heat utilization or a heating plant without electricity production is almost a rarity. However, the second thing is how the residual heat is used. An example might be the summer months when electricity demand is not falling too much down, but residual hot water ends in cooling towers which is definitely not an efficient use. But what about the hot water in the hot summer? Keep it until it finds use, how much is efficient to build a repository to be able collect water for months? This is only an example of a general problem which is energy storage. This is one of the issues needed to be gradually mastering by technological innovations in future, but before such technology will be available for common use, the improvement of technical solutions that already work and are proved to be effective is expected. An example is district heating - proven technology, but its modernization can still achieve significant savings [17, 19].

District heating were in this paper already introduced, however let's continue, and first see the following figure. It shows how important role this heating system has and especially in large urban locations.

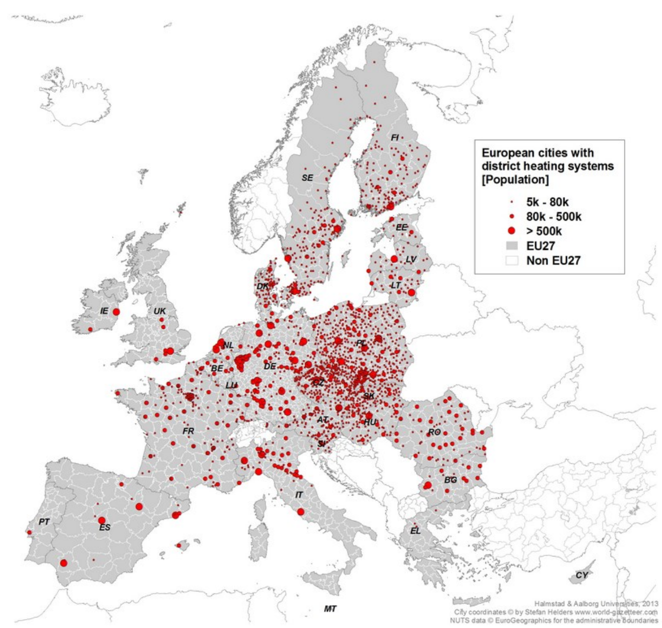

Fig. 2. European cities with district heating systems [14]

The share of individual energy input for future low temperature district heating systems is nicely illustrated in figure 3. The figure shows direction EU would like to go. With this direction, we can agree, surely it makes sense to move from primary sources to secondary, but not only to minimize the burning of nonrenewable fossil fuels, but also dependence on renewable resources should not play a dominant role in future heating systems. The leading role should take a recycling of energy and use of residual heat from other processes of human behavior (particularly industrial production)

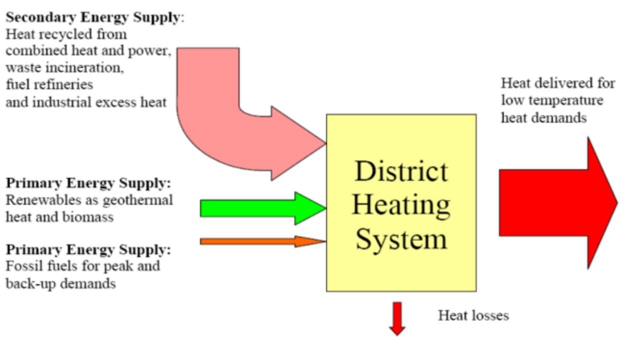

Fig. 3. DHS energy supply [15]

B. *Smart Thermal Grid*

Do not waste energy is the fact that humanity is aware for several decades. Above mentioned concept of CHP is very important, but the effort to optimize the use of energy sources must continue - as also the EU promotes in its project challenges.

Currently it is the concept of Smart Thermal Grid (STG), which efforts to use all the energy produced but also seeks the way to make this use the most optimal. An example might be the use of the sources that are in particular moment the most efficient and also effort to accumulate energy that can be produced profitably and there is no consumer for it at a given moment. This is especially applicable for the energy produced from the sun, wind and other renewable sources.

For STG is also important the role of buildings that should not be considered as simple consumers but as the objects that are able to cooperate with sources for optimum performance of the entire smart system [3].

STG can play an important role in the future Smart Cities by ensuring a reliable and affordable heating and cooling supply to various customers with low-carbon and renewable energy carriers like waste heat, waste-to-energy, solar thermal, biomass and geothermal energy. Smart thermal grids should have the following characteristics to make this possible [16]:

- Flexibility: they have to be able to adapt on a short-term to the energy supply and demand situation; in the medium-term they need to adapt by adjusting the temperature level in existing networks and through the installation of new distributed micro-networks; and in the long-term they need to adapt by aligning the network development with urban planning.
- Intelligence: they should be intelligently planned and operated, and enable end-users to interact with the heating and cooling system, for instance by supplying heating or cooling back to the network.
- Integrability: they need to be integrated in the whole urban energy system from a spatial point of view (related to urban planning parameters and processes) and from an energy system point of view (e.g. interacting with other urban networks –electricity, sewage, waste, ICT, etc.).
- Efficiency: they need to be designed to achieve the highest overall efficiency of the energy system, by choosing the optimal combination of technologies and enable a maximum exploitation of available local energy resources through cascade usage.
- Competitivity: they need to be cost-effective so that operation is affordable from a societal perspective (especially if regulated) by increasing the cost efficiency of heating and cooling supply, and creating possibilities for customers to participate. They need to be attractive for individual users by reducing energy costs, and for businesses by representing attractive investment opportunities.
- Scalability: they should be suitable for neighbourhood-level or city-wide application, according to the demand in heating and cooling and urban context.
- Security in energy supply: they should allow for increasing the security of supply at a local level by using local sources of energy for heating & cooling.

Technical elements of smart thermal grids cover thermal generation like small-scale low-carbon heating and cooling systems, CHP and new approaches for producing domestic hot water, thermal storage technologies and innovative network improvements such as new piping materials new piping layouts and non-invasive construction and maintenance of thermal networks. Network-integrated sensors and smart heat meters allow for more effective and efficient use of the separate components, supported by overarching energy management [4]. Possible components of STG are shown in fig. 4.

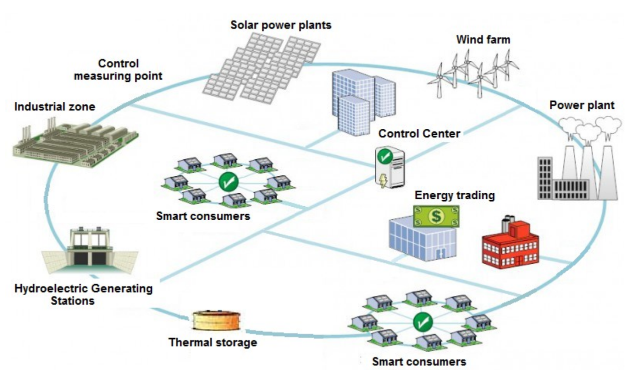

Fig. 4. Components of the STG [5]

Technical elements of smart thermal grids cover thermal generation like small-scale low-carbon heating and cooling systems, CHP and new approaches for producing domestic hot water, thermal storage technologies and innovative network improvements such as new piping materials new piping layouts and non-invasive construction and maintenance of thermal networks. Network-integrated sensors and smart heat meters allow for more effective and efficient use of the separate components, supported by overarching energy management [16].

III. Holonic System

The term "holon" and “holonic system” (HS) appeared more than 40 years ago (1967) - it was introduced by Herbert Simon and Arthur Koestler [6]. The word 'Holon' comes from the greek holos, which means whole, entire, complete in all its parts' and the suffix -on which is its neuter form, cf. proton, neutron and electron. A 'holon', in Arthur Koestlers discussions, is something that has integrity and identity at the same time as it is a part of a larger system, it is a subsystem of the larger system. “A holon, according to Koestler is a model-component with a "Janus-face" - one side looking "down" and acting as an autonomous system giving directions to "lower" components and the other side looking "up" and serving as a part of a "higher" holon. Apart from hierarchic systems (as in business or military organisations), the different holarchic system levels consists of each other, they are subsystems (or supersystems) to each other. When the subsystems join in a supersystem, new characteristics emerge that can't be deduced from the qualities of the subsystems (emergence). In the same way as we cannot describe a human as a 'supercell', we cannot describe an ecosystem as a 'superorganism' or the ecosphere as a 'superecosystem'. They are different objects with some characteristics that not can be derived from the characteristics of the subsystems [13].

A. *Holons and Agents*

Suitable explanation for HS is to liken it to multiagent system (MAS). It is therefore assumed that term MAS is for readers, at least in general terms known.

Nevertheless, semantically, an agent and a holon have very different meanings and uses. In general, the word “agent” has multiple meanings, but the following meaning from Webster’s Collegiate Dictionary is the most appropriate [12]:

“An agent is one that acts or has the power or authority to act.” In other words an agent is a singular entity with the authority that is empowered to accomplish its purpose.

The term “holon” describes self-contained elements that are capable of functioning as autonomous entities in a cooperative environment. Holon is a fusion of the Greek word “halos” meaning whole and the suffix “on” denoting a particle. In a holonic system, each holon works with all other holons to deliver an overall system objective. The underlying point here is that an “agent” has the right to make decisions for its own purpose, whereas a “holon” can only act with respect to a collective (or holarchy) of holons to which it belongs and thereby provide a collective or system autonomy, as opposed to a collection of individual autonomies. One of the most important properties of Holon is recursion. Holon unlike agents can in their structure contain other Holons with the same or a different architecture. Holons are therefore autonomous, cooperative and partly intelligent modular blocks which are functional within decentralized control. The agent is elemental decision unit that collects and processes the data and knowledge. It is not physically tied to technology.

To design a distributed software system, as with any other solution paradigm, it is useful to follow guidelines. First, let’s summarize the major differences between multiagent and holonic systems:

Scope: agents are focused on local issues while holons are focused on global issues.

Independence: holons are not independent whereas agents can exist functionally independent of other agents.

Relationships: holons cooperate with other holons, whereas agents need not be cooperative; in fact, agents can compete with other agents.

The choice whether the holons or agents are used for the system control will be determined by the point of view that is taken. More specifically, HS can be considered to be a paradigm for distributed intelligent control, whereas MAS is regarded as software technology that can be used to implement HS [11].

B. *Properties and applying of Holon*

In recent years the concept of holonic systems expanded, elaborated and applied inter alia in the field of production systems, especially in discrete manufacturing. It is one of the concepts applicable to distributed manufacturing systems and their management, but it has also potential for use in other industrial areas.

The term holarchy refer to a set of holons including their mutual relations. Holarchy is a system of holons that can co-operate to achieve a goal or objective. The holarchy defines the basic rules for co-operation of the holons and thereby limits their autonomy [7]. The concept of holarchy is illustrated in the following fig 5.

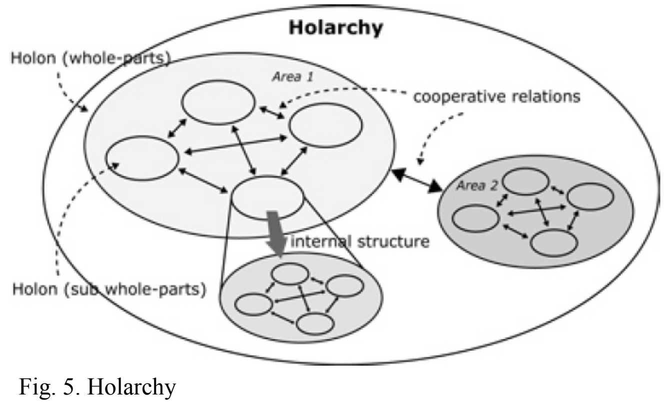

Fig. 5. Holarchy

Holon, in this context, could be defined as an autonomous and co-operative building block of a production system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon. It is also possible to see it as a model of a particular element, i.e. part of the model of the entire system. In this sense is holon used in this article.

As was mentioned above, the internal structure of holons can be made up of a group of other holons, which can be described as "subholons". Any such subholon is, of course, full holon. This allows a very flexible way to define entire holonic system.

Once more it is relevant to underline, that the most important features of holon are autonomy and co-operation. Autonomy is characterized by its ability of self-regulation, i.e. the capability to apply the flexible strategy which allows holon to respond differently to changes in its relevant environment. This ability to respond individually to changing conditions in which holon work, must be connected with a certain degree of intelligence to its reaction to change and adapt to the demands of the environment to be efficient and effective. Cooperation takes place between holons using the corresponding parts "subholons" of each holon - the parts that have the ability to implement relevant cooperation.

Good co-operation requires good communication between holons. Holon exchange information with other holons throughout holarchy. This direct, mutual communication between holons manifests an important distinction between distributed systems management and centralized management systems. In centralized systems, all communication takes place via a central element of the control system.

IV. Holonic Model of DHC

Creating a holonic model the system comprises a series of specific steps - for the DHC system as follows:

A. Split system into Holons and the creation of Holarchy

This is based on an analysis of the modelled system in which it is necessary to carefully and thoroughly assess the structure of the modelled system, carefully identify individual holons including their internal structure exploits the use subholons. It is also necessary to analyse the relationships and bindings between holons. All of these steps should result into a suitable split of the system into holons and creation of appropriate holarchy.

B. Specification of particular properties of holons

The aim of this step is to specify particular properties of individual holons and, if relevant, also define their inner structure.

When specifying the properties of individual holons, it is necessary to take into account the nature of the modeled system, i.e. what characteristics of the behavior of the system will be with the support of the prepared model analyzed. For each of these characteristics must every holon associated with such characteristic contain a set of methods, techniques and algorithms that allow to quantify this characteristic as accurately and completely as possible.

In the case of the DHC will be typically monitored and analyzed the ongoing processes on both, the technical and economic terms.

From the technical point of view the model, and thus holons modeling the individual elements of DHC, will usually contain mathematical and physical description of the involved processes. On this basis will be determined the characteristics of the individual elements. Also will be determined the operating ranges limits of various physical quantities associated with these characteristics. These are e.g. limits of the thermal energy delivered by the source, depending on factors affecting the production (e.g. irradiation with solar thermal energy), or limits for the amount of thermal energy transferred by the distribution elements.

In terms of economy, the model will include a description of the economic variables and their calculation, depending on the value of the influencing factors. It is e.g. the determination of prices of produced thermal energy unit by the source (of course as time function), determination of the heating costs for the particular consumers (again as a function of time), etc.

C. Specification of services

This step focuses on the specification of individual holon services which are offered to all others holons. Each holon performs within the system some specific, clearly defined activities and the results of these activities are offered to other holons as a specific services. Supply and use of these services is closely related to the implementation of essential holon characteristics - autonomy and a cooperative.

To guaranty administration of these offered services is a need to be developed and used appropriate communication system. Such system has to allow holonic model to: Communicate between any holons which may be located anywhere on a computer network. Initiate communication between two holon to any of them. This is due to the requirement of strict compliance with the principles of distributed systems, where all elements are "equal", at the same level. Each holon, which offers its service can make such offer to others holons either on its own initiative (e.g. when it is able to carry it out) or on demand from the potential user of this service.

One possible solution is to use a standardized mechanism for Web services, respectively semantic Web services or WCF framework [8].

An example of model preparation will be demonstrated on CHP source, see schematic diagram in fig. 6. Next figure shows holarchy and particular services for supply (offer) and demand for the selected system.

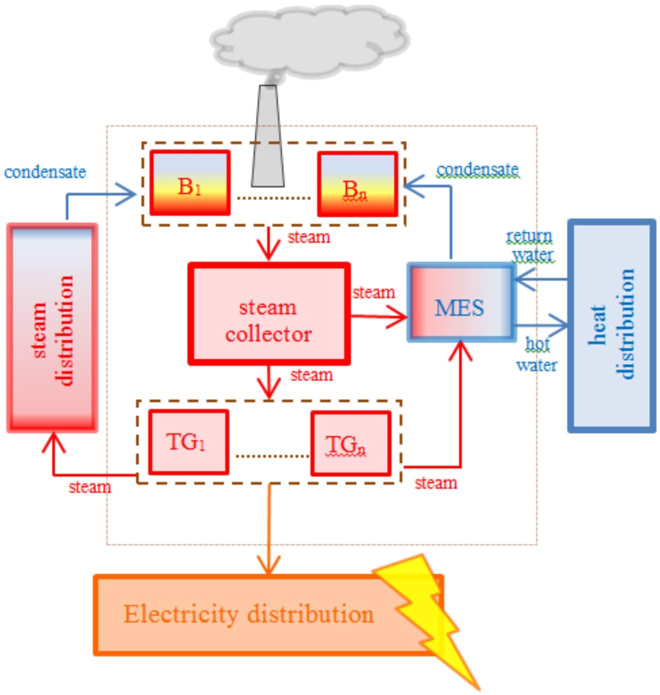

Fig. 6. Simplified diagram of the basic elements of the CHP plant

Where:

$B_{i..n}$ are boilers,
$TG_{i..n}$ are turbo generators,
MES main exchange station.

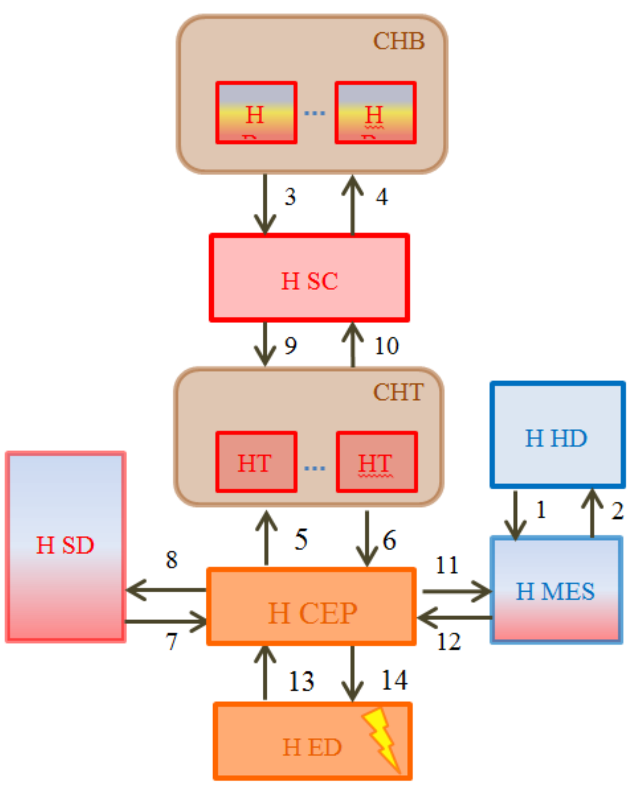

Fig. 7 Holarchy of the control system

Where:

CHB … container of boiler holons
CHT … container of turbines holons
HB … holon of the boiler
HT … holon of the turbine
HSD … holon of the steam distribution
HSC … holon of the steam collector
HHD … holon of the heat distribution
HMES … holon of the main exchange station
HCEP … holon of the cogeneration electricity production
HED … holon of the electricity distribution

Description of individual services in figure 7:
1 – Demand on predicted amount of "primary" steam for direct distribution
2 – Offer achievable (free) amount of "primary" steam for direct distribution
3 - Offer achievable (free) amount of "primary" steam for steam collector
4 - Demand on predicted amount of "primary" steam for steam collector
5 - Offer achievable (free) amount of "primary" steam for heat exchanger
6 - Demand on predicted amount of „primary“ steam for heat exchanger
7 – Demand on predicted amount of steam for direct distribution
8 - Offer achievable (free) amount of steam for direct distribution
9 - Offer achievable (free) amount of steam from the steam collector for cogeneration
10 - Demand on predicted amount of steam from the steam collector for cogeneration
11 - Offer achievable (free) amount of steam for main exchange station
12 - Demand on predicted amount of steam for main exchange station
13 – Offer achievable (free) amount of electricity for direct distribution
14 – Demand on predicted amount of electricity for direct distribution.

V. METHOD FOR CONTROLLING DHC

The processes associated with the production, distribution and consumption of thermal energy in DHC, especially if the system included a large dominant source, have in terms of their timing a specific behaviour. They are reacting relatively slowly and between their individual parts is quite various and non-negligible delay - traffic delays. This significantly affects the way of control of the entire DHC. On the one hand this simplifies the implementation of control actions (there is "enough time" to make it), but on the other hand it complicates the control strategy - it is necessary extensively to predict the behaviour of system (e.g. when the heat is produced, it is already necessary to predict its amount, what will be needed in order a few hours, which will last transfer of heat media to the point of its consumption.

In view of the above, it is possible to specify a three-stage process of DHC control:

- *Prediction phase*. This stage concerns the determination of time course of the selected technical characteristics of the individual parts of the system. For their determination is usually used a combination of the above mentioned mathematical and physical models, and analysis of historical operational data. Prediction context must be understood sufficiently broad, because it involves all parts of DHC:

  a) The most important is the prediction of heat consumption in individual consumers in time and depending on a number of external factors - climatic conditions, the nature of the operation of individual consumers, etc.

  b) Very important is also the prediction of the amount of heat possible to be produced by individual sources, again depending on the time and range of internal and external factors - energy from renewable sources, depending on the sunlight, wind strength, the configuration of the technological equipment and the dynamics of their changes in the classical sources using combustion processes, etc.

  c) It is considerable important to predict time possibility of the heat distribution, respectively its ability to transfer the required amount of thermal energy in required time.

- *Optimization phase*. At this stage, it is necessary on the basis of the whole complex of predicted data to determine the best division of supply of heat between different producers and consumers. Here are mostly applied above mentioned economic variables. The objective function to optimize is mostly the cost function whose minimum is searched.

  At this stage of the control considerably appear the benefits of the holonic concept, i.e. distributed system. Optimization can be very easily divided to solution at different levels - individual holon, suited holons groups and for the entire holarchy. For the optimization in higher level it is possible to use results from lower level, which are easily calculable.

  Algorithm optimization calculations is based on the fact that individual consumers are demanding at all (technically possible) producers whether they are able to meet its requirements for heat supply in quantity, or even the quality spread over time. Quality means the temperature of the heat transfer medium - however, this option is very limited by distribution network layout. Contacted suppliers will evaluate and weigh their possibilities and make an offer to consumers - under what conditions, usually economic, or with which restrictions may be quoted energy supplied. In the simplest variant, the consumer compares each relevant offer and chooses the one, which is most suitable for its needs. Suppliers then have the opportunity to influence their profit through their offerings. In more complicated cases, the optimization is conducted with respect to the specified groups of holons or to whole holarchy. Disclosed algorithm in this case is supplemented by iterative procedures for finding the optimal value of the more complex formulated objective function.

- *Implementation of control actions*. At this stage of the control process has been ongoing for quite classical approach when control interventions determined by the prediction and optimization phase are applied using the appropriate technical means

For the practical implementation of DHC control is necessary to resolve the issue of time synchronization of the phases of the control process. This is relates to the fundamental specific problem, that prediction, eventually optimization takes place at a different time of the controlled system long before the application of control interventions. The time difference, which is due to the time needed to transfer the required amount of heat exchange medium from the point of production to point of consumption. This is the dynamic variable that has a large divergence, depending on the number of internal state variables of the system.

VI. Conclusion

Building and deploying Smart Thermal Grids into practice requires a number of steps. Besides upgrading hardware and improve communication and measurement is necessary to ensure that elements of the system together and collectively came to the efficient use of resources. The article tried to show that in such a heterogeneous environment, it is advisable to implement a distributed system management. And one of the options is to use holonic concept – concept of independent but also cooperative elements in the environment of the joint information network.

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