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Interconnectivity between energy and water supply systems

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Abstract. Water and energy are basic resources for humanity. As the processes of providing these resources have a major contribution to intensifying climate change, there has been a growing interest in finding ways to balance the demand and consumption of these resources, strengthening the resilience of these systems to socio-economic and environmental disturbances. This paper analyses the characteristics of interconnectivity between two systems – energy supply system and water supply system. The connections between demand and consumption of water and energy in these interrelated supply systems are highlighted at the level of EU and world regions. The concept of Water-Energy Nexus is introduced and different models and indicators are described. The specific energy indicators on "energy for water" are analyzed for the case of urban water supply systems and ways for energy efficiency increasing are established.

Keywords: water-energy nexus, models, indicators, energy for water, interconnectivity.

1. Introduction

Water and energy are the main resources that define sustainable development of the cities, and their future development depends on the efficiency, co-management and resilience at socio-economic and environment constrains [1], [2].

The growths of the level of urbanization, the increase of the quality of life, as well as the economic development, have lead up to a growing demand for water and energy [3], [4]. Energy and water systems have an important contribution to intensifying climate changes and climate instability, thus, there has been a growing interest in finding ways to balance the demand and supply of water and energy, especially at the urban level [5]. One of the sustainable development goals adopted by the United Nations in 2015 is to provide equitable and universal access to drinking water for the world's population by 2030. But this means increasing water

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consumption and thus increasing energy consumption. The lack of energy efficiency leads to an increase in the rate of carbon emissions (CO_2/kWh) in the atmosphere. Thus, it is imperative to design, build and manage new water supply systems with smaller energy consumption, higher effectiveness and reliability, in order to reduce on long-term the greenhouse gas emissions [1], [6].

Water-Energy interrelation, also known as Water-Energy Nexus (WEN), is a multidimensional interconnection, provided with a technical and non-technical nature, the common points being the two sectors of production, transport, distribution and use of water and energy.

There are many research papers which analyzed the factors that influence WEN, the specific indicators that can properly reflect the ways of the energy efficiency increasing and the economic and social growth taking in account the environment requirements. The complexity of this multidisciplinary approach, consisting in the correct evaluation of the technical factors (energy consumption, pressure, temperature, flow, etc.) and of the non-technical factors (urbanization, climate change, etc.), requires new approaches and knowledge systematizations. It is expected to reveal new contributions on how to implement sustainable development, especially in large urban agglomerations.

The paper analyzes the demand for water and energy and the factors that influence consumption in these sectors. It was found that most of the time research treats water and energy separately, this fragmentation being explained due to different monitoring and control methodologies applied and significant differences in the data structure of the management applications. In more detail, the energy indicators that define the WEN interconnectivity in urban water supply with energy supply systems are introduced. The specific indicators on “energy for water” in the case of water pumping stations as main component of the water supply systems are analyzed and ways for increasing the energy efficiency are highlighted.

The paper can serve as an overview for future developments on how to define and implement methodologies for the synergistic development of the two sectors, taking into account the socio-economic and environmental constraints.

2. Demand and consumption of water and energy. Interconnectivity

2.1. Interrelated water and energy supply systems

The water supply system and the energy supply system are two systems which have many differences in their infrastructure, specific processes, particular data structure of management applications and different monitoring and control methodologies. However, there are many similarities [7]: the infrastructure of each system includes the chain of production, transportation, distribution and use; the flow direction of the two resources is similar, from environment (water and energy resources) to user (industrial, commercial, domestic, agriculture, etc.). Fig. 1 illustrates the similarities between the technological lines of the two sectors.

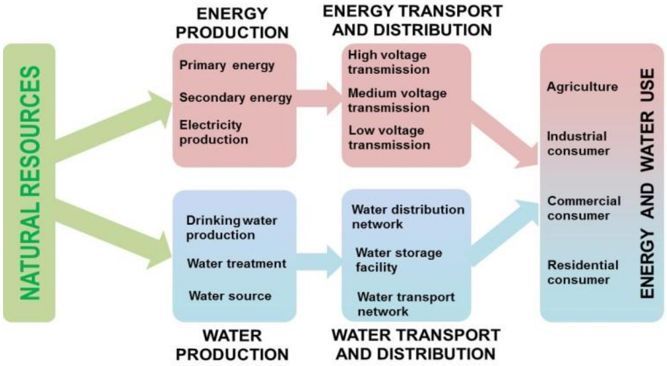

Fig. 1. Similarities in the infrastructure of the supply systems of production, transport and use of water and energy

The interdependence between water and energy supply systems is obvious: modern water supply systems cannot operate without energy, and energy supply systems cannot operate easily without water. Thus, recent studies consider the current water and energy supply systems as coupled systems, the level of interconnections being in function of the degree of coupling between the two systems [8], [9].

The interconnection is intrinsically reflected by the relationship between demand and consumption of water and energy. The terms "water for energy" and "energy for water" are used to indicate the water requirement for the energy sector and the energy requirement for the water sector. The evolution of water and energy demand and consumption in different regions of the world is further analyzed.

2.2. Water demand and consumption for the energy supply sector

Water is needed for almost all phases of energy production: for fossil-fuel extraction, transport and processing, and power production [10]. Water is needed for hydropower plants, tidal power plants, cooling water for thermal power plants and nuclear power plants, power storage systems. Energy can be also produced as a by-product from wastewater treatment [11].

The EUROSTAT Report shown that in the period 2000-2015, for European Union countries, water used for electricity production was about 70-80 billion cubic meters/year (bmc/year), that correspond to nearly 30-35% of total EU water withdrawal, which oscillates between 120 and 170 bmc/ year.

The technical report published in [10] provides a future projection of fresh water demands by EU energy sector, estimation based on models that consider data for water extraction and consumption in combination with the evolution of technologies for obtaining electricity.

The water withdrawals are always greater than the water consumption. Water withdrawal or gross water abstraction is the amount of water removed from the ground or diverted from a water source for use in any energy process. Water consumption or net water abstraction is the amount of water withdrawn that is not returned to the source - the amount of water that is evaporated, transpired, incorporated into product or crops, or otherwise removed from the immediate water environment [5].

In Fig. 2 the prognosis of water withdrawn and water consumption required by the energy sector in some EU countries is presented [6].

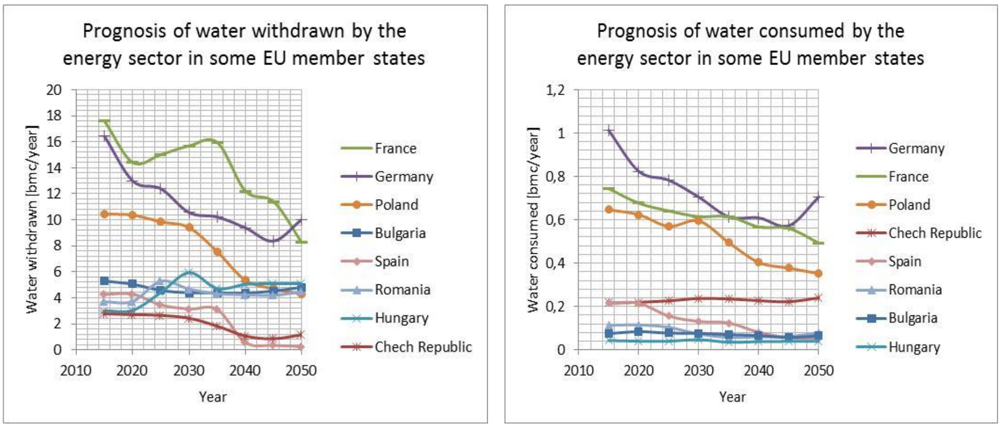

Fig. 2. Prognosis of water withdrawn and consumption by the energy sector in some EU member states (years: 2015 – 2050)

Data show that in 2015 the largest water withdraws demanded by the energy sector took place in France, Germany and Poland. With these scenarios, it is expected that the water withdrawal will decrease of 12% by 2030 and of 38% by 2050 (about 46 bmc) compared to 2015 level (about 74 bmc).

In terms of water extraction and water consumption needed by the global energy sector, we should add that although water resources on Earth are abundant, fresh water resources still account for only 2.5% of global water resources [10].

Global freshwater withdrawals from surface water and groundwater sources have increased by roughly 1% per year since the 1980s as demand in developing countries has surged, and groundwater supplies are being systematically diminished by a rate of extraction at 1-2% per year globally, exceeding the recharge rates.

Recent studies are related to the prognosis of water demand for the energy sector at the world level. Data from the Table 1 are obtained having as basis the year 2014. The global energy-related water withdrawals are expected to increase by less than 2% to 2040, and water consumption for energy sector will rise by almost 60% compared to 2014 [1], [6].

The data predict that in 2040, the global water demand and consumption in the energy sector significantly grow in Asia and Africa. In developed countries, in recent years, water consumption is at a level and even has a negative dynamic due to the measures taken to optimize the management of water resources.

Table 1. Global water demand and consumption in the energy sector by 2040

Regions	**Water withdrawal [bmc/year]**			**Water consumption [bmc/year]**		
	2014	**2025**	**2040**	**2014**	**2025**	**2040**
Unites States	141	121	103	14	17	15
Europe	46	38	35	5	4	4
Asia	92	101	140	15	23	37
Middle East	3	4	5	2	2	3
Africa	6	5	11	1	2	2

Notes: The water quantity is measured in billion cubic meters (1 bmc = 10^9 m^3); Data according to https://ourworldindata.org/water-use-stress

For developing countries, global water consumption is on the rise. This is also the case in China, where the weight of water consumption for energy sector is with 33.91% higher than in 1962.

2.3. Energy demand and consumption for water supply sector

Energy is needed for water extraction, treatment, transport and distribution, collection and treatment of wastewater, desalination, data monitoring process [11]. In Table 2 and Fig. 3, the prognosis developed by the IEA agency for the dynamics of the energy demand for the water sector, forecasted for 2030 and 2040, compared to the reported year 2014, is presented [4], [11].

Table 2. Global electricity demand for the water sector by 2040

Global electricity demand	**Year**			
	2014	**2020**	**2030**	**2040**
Energy for water extraction from groundwater and surface, TWh	333	352	364	368
Energy for water distribution to the consumer, TWh	180	195	201	205
Energy for desalination, TWh	41	56	186	345
Energy for wastewater treatment, TWh	195	222	266	314
TOTAL, TWh	749	825	1017	1232

Note: The electricity is measured in teraWatt hours (1 TWh=10^{12} Wh).

The studies projected that by 2040 the electricity needed for desalination processes will equal the energy requirements for water supply from groundwater and surface freshwater.

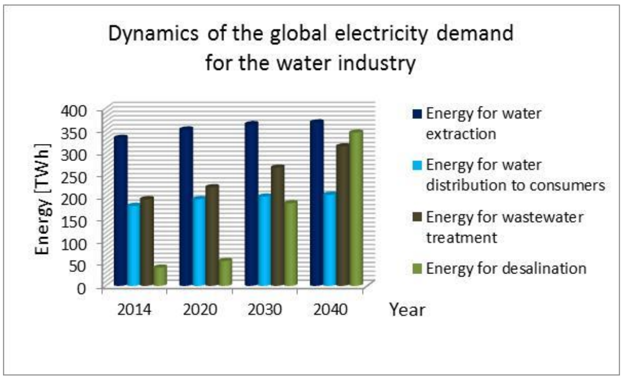

Fig. 3. Dynamics of the global electricity demand for the water industry until 2040
Data according [11], at: https://www.iea.org/articles/introduction-to-the-water-energy-nexus

The increase of energy demand for the water systems highlights the importance of measures to increase the energy efficiency to preserve both water and energy.

A synergistic operation of these systems can be done by considering all the interconnections between these two systems.

3. Defining and describing the Water-Energy Nexus (WEN)

An interconnection on water-energy-food was first discussed at the Water-Energy-Food Conference in Bon in 2011. Starting from the fact that water, energy and food are the three interdependent and interrelated mankind needs, the connection between these elements has been called the Water-Energy-Food Nexus (WEFN) [12]. Since then, the concept of Nexus has expanded and been used to describe the interactions between various other elements.

The interrelationship with environmental factors was highlighted, analyzes were made at city, region, country or global level, with the development of research methods and the introduction of quantitative and qualitative indicators.

In order to highlight the complex interactions between water, energy, food and other elements of the ecosystems, this article further examines the interdependencies between water and energy, as basic elements that support the sustainable development.

3.1. Water-Energy Nexus

The interaction between water and energy has been the subject of numerous studies that have shown that the two elements - water and energy - are interconnected through complex relationships at the local, regional, global level. This phenomenon has been called Water-Energy Nexus (WEN) [7].

WEN plays a vital role in redesigning, planning and developing the urban regions for present and future demands. This concept is complex due to many interconnected variables of technical and non-technical contexts [13].

A bivalent relationship between water and energy can be obtained by analyzing the need for water - "water for energy" - to produce energy from various sources (fossil fuels, biofuels, nuclear energy, wave energy, etc.) and the energy needed to obtain drinking water and for other uses - "energy for water" - in modern water supply systems (for extraction, treatment, transport and use). A synthetic overview is described in Fig. 4.

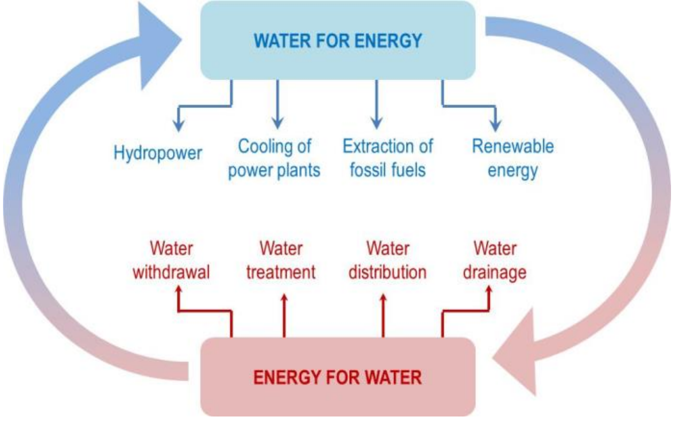

Fig. 4. Bivalent relationship in WEN connection

However, such interrelation does not describe the multidimensional, technical and non-technical nature of WEN. The interactions between water and energy supply systems have amplified and differentiated due to the increase in demand and consumption in both systems and the multiplication of economic, social and environmental constraints [14]. Various WEN models have been developed to describe these interconnections.

3.2. Models of WEN interactions

A. *Mega-system model*

The study of the current water and energy systems, considered as coupled systems, allows the appreciation of the degree of WEN interconnection by evaluating the degree of coupling between the two systems [9].

The WEN “system of systems” model is considered in [8], [15], [16] in which the concept of micro-grids is extended to the water supply system. Fig. 5 shows the block diagram in the case of a power grid that uses some of the electricity to operate the water supply system.

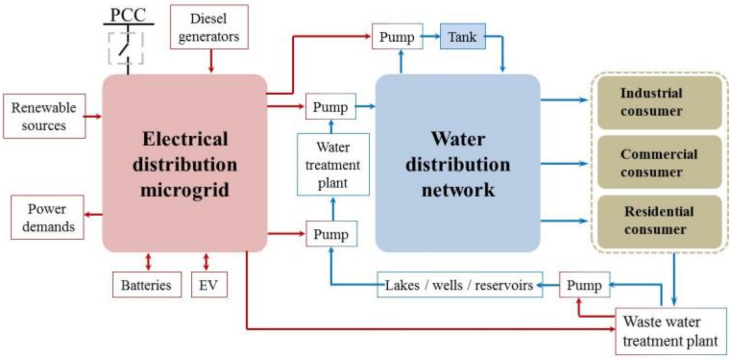

Fig. 5. WEN model with micro-grid concept extension (according to [8])

Pumps, tanks and irrigation systems can be used to create virtual energy storage units for the electricity grid, to mitigate the shock on the microgrid in the event of an energy imbalance [15].

There are advantages in the WEN approach by considering the concept of system of systems - Mega-water-energy system consisting of two systems:

- The two systems can be treated as “black box”, for which the energy and water balances are drawn up, taking into account the related input and output quantities, in static or dynamic regime [17];
- Optimizations can be made separately for the two systems, and at a later stage the interdependence between them will be taken into account. The model can be extensively applied to a smart building, a village, a city or a larger community;
- A specific delimitation of the system's boundaries allows highlighting the cumulative losses of water and energy that lead to the reduction of the natural water resources of a region [9].

However, these bivalent relations between the two systems does not describe all the connections and dynamics of WEN. A more detailed analysis of the two systems illustrates the multiple connections between them (Fig. 6).

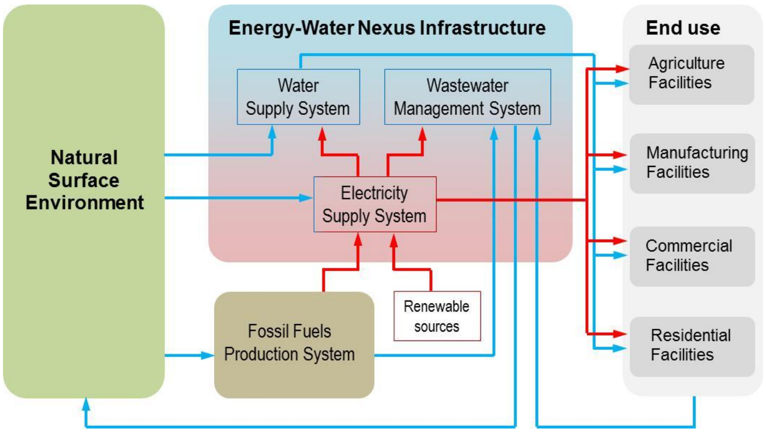

Fig. 6. WEN inter-system connections for water and energy supply systems (according to [17])

This model describes WEN infrastructure with specific directional connections, showing the flow of water and energy resources, from environmental resources to consumers. For water, the flow from consumers to the natural environment is also indicated. The infrastructure for the energy system is not detailed, because in this study only the "energy for water" component is of interest.

B. *WEN connection and smart systems*

Efforts are currently being made to develop smart electricity distribution networks. Similarly, modern water supply systems are beginning to integrate smart metering systems, which are the starting point for the development of smart water systems and potential means for achieve systems with higher efficiency, effectiveness and reliability (Fig. 7).

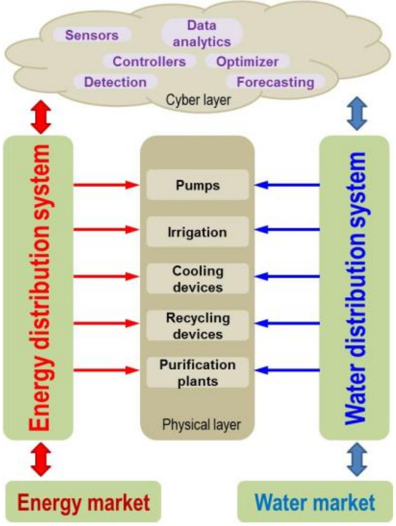

Fig. 7. Block diagram of a smart WEN integrated system [15]

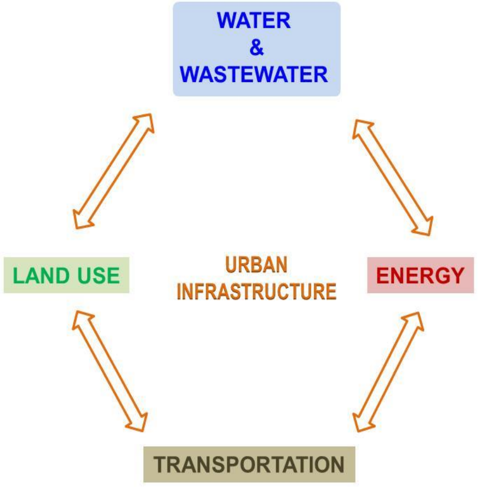

Fig. 8. Urban infrastructure and interactions between components [19]

The linkages include the connection with the energy and water market, as well as the connection between the physical layer of the water supply system and the cyber layer considering the means for online monitoring, control and process optimization. Through robust design and the application of appropriate planning procedures, the two systems can be resilient under normal operating conditions and with low disturbances [14]. However, an integrated treatment can be done if the physical models of the two systems will be considered, taking into account the multiple interconnections between them.

C. *Integrative models*

At the technological level, there have been attempts to optimize the connection points between water and electricity systems, in order to reduce the energy intensity of the technologies in the water system and the amount of water used in the energy system [9]. In [18] an integrative treatment of the WEN linkage is proposed, as shown in Fig. 8. The integrative models have been proposed especially to urban water supply systems, to substantiate an integrated management system. A holistic treatment in the case of the urban infrastructure development plan is also proposed in [19]. This model can describe the interdependence between each element of urban infrastructure, demonstrating that appropriate decisions are needed for the development of urban infrastructure taking into account all the factors that influence the sustainability of a city.

In [20] a model was developed to evaluate the water-energy-land use connection from an energy perspective, based on bidirectional connections.

Thus, in making decisions about the implementation of urban infrastructure, studies are needed on how land use, water infrastructure, energy infrastructure and transport infrastructure interact, as well as other factors such as socio-economic factors, the environment and the implementation of sustainable development policies [21].

However, the implementation of the integrated models involves it seems the introduction of all process digitization, a major solution in order to ensure coordination at the community level.

3.3. Factors affecting WEN in urban area

The urban supply systems must meet the challenges of the 21st Century: urbanization, climate change, supply and demand, global population growth. These factors also affect the connections between water and energy [13].

A. *Urbanization.* Urbanization affects energy and water resources in different ways. Thus, the hydrological system is affected by urbanization through floods in the lower areas of cities, lack of water, changing rivers, water pollution. The population density in urban areas is higher, which also means higher energy consumption, implicitly higher CO_2 emissions. Urbanization, as it is currently understood and promoted, leads to increased energy consumption, increased greenhouse gas emissions and environmental pollution.

B. *Climate change*. Reports of IPCC [2] show that the increase in the temperature of the Earth's surface, referred to as "global warming" or "climate change" has occurred since the beginning of the pre-industrial period. A rise in temperature by 1.5 - 2.0^{o}C has a dramatic influence on water, energy, food, housing, and ultimately on life on Earth. Climate change is putting pressure on local energy production and drinking water supply.

C. *Demand and supply.* The interrelation of water - energy means the impact of one element on the other. High energy demand means higher water consumption and vice versa: high water demand for the industrial, agriculture, residential sectors increases the amount of energy needed to extract, treat, transport and distribute water. The balance between supply and demand determines the cost, which includes the environmental cost.

D. *Population growth.* Population growth leads to an increase in water and energy consumption, which leads to the impoverishment of these resources in their original form. In developing countries there are problems with excessive increases in carbon emissions that affect other factors and processes.

This analysis proves that the water-energy interconnections (WEN) can have negative or positive meaning under the influence of urbanization, climate change, supply and demand, population growth. All these factors need to be considered in WEN optimization, to ensure an appropriate socio-economic and ecological balance.

3.4. Indicators of WEN in water supply systems

The indicators that characterize WEN in water supply systems must allow comparisons both within the same system and in the case of sets of systems [22], to be as universal as possible, independent of particular conditions of use, easy to understand, objective and avoid personal or subjective interpretations. The existing WEN indicators, applied to urban water supply system, can be grouped into:

- Technical indicators, which assess the functionality of the system,
- Economic indicators, which are related to the cost of energy,
- Environmental impact indicators, such as CO_2 emissions,
- Investment indicators, which substantiate system design and implementation.

But such groupings of indicators do not provide a complete description of the dynamics of WEN links. Thus, a transdisciplinary treatise on this issue is needed, in which the WEN link is framed as a process that begins with “what exists”, continues with “what we can do”, goes to “what we want to do” and results in “what do we have to do” [23]. In many studies, the main WEN indicators used are: electricity consumption (kWh /inhabit.year), water availability (mc water /inhabit.year) and the remaining organic load (kg /inhabit.year). All these indicators are calculated and represented in units per capita to facilitate the comparison between the different sizes of the population and the area [13], [24]. For example, the United Nations studies have estimated in 2015 that water availability per capita should be higher than 2500 mc water/inhabit.year to maintain aquatic ecosystems, social and economic human activities. Population density and urbanization level are the main factors pressuring water availability.

As application, in the next chapter, the energy WEN indicators on the side „energy for water” of an urban water supply system are analyzed.

4. Energy WEN indicators for urban water system assessment

4.1. Energy transformation method

Regarding the “energy for water” component of the urban water supply system assessment, numerous methods have been developed in recent years to assess WEN interconnections, based on the analysis of the transformation of energy in the processes of water production and distribution to consumers. This method considers that in all physical and chemical processes related to water flow, energy transformations occur.

The energy for a water supply system originates from a natural surface or groundwater source, is described by the natural water level (e.g., streams, reservoirs, or aquifer head). Usually, this energy is not sufficient to supply water to the users. It is therefore necessary to provide an additional energy from other sources, usually electrical energy.

This energy is transformed into kinetic and potential energy of water to ensure proper operation of the system, providing water for all users. But, in all thermodynamic processes, energy dissipation occurs during transformation. Energy losses are developing in pumps, friction in pipes, water losses, maintenance of a higher pressure than required, etc. [14], [25].

Fig. 9 shows a scheme of energy transformation in water supply system: electric energy, to which may be added natural hydroenergy, is used to drive mainly pumps for water extraction, treatment and distribution to consumers. For each stage of transformation, the electrical, mechanical, hydraulic ΔE energy losses are highlighted.

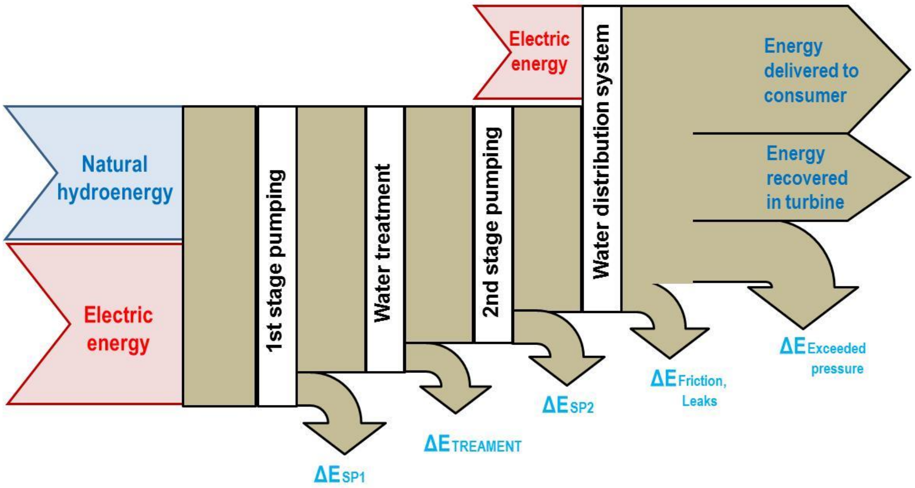

Fig. 9. Scheme of energy transformation in a water supply system

This scheme allows to build different energy balances and to define specific indicators, which could be used for better planning of actions to increase energy efficiency. The equilibrium equation between the input energy and the output energy from the water supply system is:

$$\sum (E_{el-imput} + E_{hydro-imput}) = \sum (E_{el-convert-output} + E_{hydro-convert-output}) + \sum \Delta E_{losses} \quad (1)$$

On the basis of the energy audit, the specific indicators are defined. In [22] five indicators were determined for a water supply system: excess in supplied energy, network energy efficiency, energy dissipated through friction, leakage energy, and standard compliance.

4.2. Specific energy indicators for water supply system assessment

Energy assessment of a water supply system may concern all processes - in the extraction, treatment, distribution of water, sewage disposal and treatment, or some parts of water system. Usual, the assessment is conducted using indicators which are based only on data collected in water utilities [14], [26], [27].

A practical methodology of performance assessment of water utility was developed by the International Water Association (IWA) and described in the IWA Manual of Best Practice Performance and Indicators for Water Supply Services [22]. The IWA manual referred to 166 indicators, divided into six groups. The following indicators related to energy were specified in the physical indicators group:

- percentage of pump capacity used,
- standardized energy consumption,
- reactive energy consumption, and
- energy recovery.

The assessment is based on electricity consumption data (read from meters) for all devices, such as pumps, blowers, heating, ventilation, and air conditioning installations, lighting, etc.

In the case of pumping stations, pumps are widely used to extract and transfer water from rivers and reservoirs to higher elevations facilities for treatment, distribution, or utilization. The amount of input energy required for water pumping depends primarily on three factors:

- elevation difference between the water abstraction and delivery points,
- amount of pumped water, and
- efficiency of the hydraulic and electric system of pump.

The following indicators are used to describe the interconnections between water availability (i.e. river flow and reservoir storage) and energy pumping capacity:

- Annual pumping energy, PE_A:

$$PE_A = \sum_{i=1}^{Y} PE_i \tag{2}$$

- Lowest daily pumping energy, *LDE*:

$$LDE_A = \min\{PE_1, PE_2, ..., PE_Y\} \tag{3}$$

- Highest daily pumping energy, *HDE*:

$$HDE_A = \max\{PE_1, PE_2, ..., PE_Y\} \tag{4}$$

- Variability in pumping energy, characterized by variability coefficient, CV_{PE}:

$$CV_{PE} = \frac{\sqrt{\frac{\sum_{i=1}^{Y}(PE_i - \overline{PE})^2}{Y-1}}}{\overline{PE}} \tag{5}$$

In these relations:
PEi is the pumping energy in the *i*-th day of the year;
Y is the number of days in the year;
$\overline{PE}$ is the mean daily pumping energy in a certain year, in GWh/day.

Energy intensity *EI* is a global indicator that characterizes the technical dimension of WEN for pumping station and it is defined by the relationship:

$$EI = \frac{PE_{\mathrm{A}}}{WV_{\mathrm{A}}} \tag{6}$$

where: PE_A is annual pumping electrical energy consumption; WV_{A} is the pumped water volume. Energy intensity is directly related and influenced by the total efficiency of the pumping system, water losses and water demand.
For the considered water supply system, Molinos et al. [28] obtained energy intensity with values between 0.07 and 0.21 kWh /mc, which are close to the average values obtained at various installations in the world.

4.3. Energy intensity in pumping stations

For assessment of energy intensity in a pumping station, a drinking water pumping station is considered. The characteristics are described in [29]. For a period of a month (30 days), the electricity consumed by a pump group was monitored at one-hour intervals, and the flow of water delivered to the consumers at one day intervals. To obtain the dynamics load curve of electric energy and the water flow curve, data processing was done applying experimental statistical method (statistical average, standard deviation and variation coefficient). The relations (2) - (6) are used to obtain energy indicators (Table 3).

Table 3. Energy indicators for water pumping station

Energy indicators	Value	Standard deviation [%]
Average daily electrical energy consumption [kWh/day]	423.09	± 19.02
Average daily flow of water delivered [mc/day]	669.12	± 30.08
Total electrical energy consumption [kWh]	13116	
Total water delivered [mc]	20743	
Energy intensity of pumping station [kWh/mc/month]	0.632	

For the considered pump station, the value obtained for the energy intensity $EI = 0.632$ kWh/mc/month is much higher than the average values obtained for other different installations in the world [28]. Measures are needed to be taken in order to increase the energy efficiency for this water pumping system.

5. Conclusions

Water-Energy Nexus is a new field of study, which has gained consistency through the ability to capitalize synergistically and simultaneously on the issue of sustainable governance of natural resources. The analysis shows that there is a growing interest in using the WEN concept in the water and energy sectors.

Many models of WEN interactions have been developed and the factors which affect the WEN dynamics are identified.

But, most of the studies focused on analyzing the connection between these sectors on the supply side, with an emphasis on streamlining the processes which take place: water withdrawal, treatment, distribution, recollection.

Specific indicators are used to assess WEN in water supply systems. Energy intensity *EI* is a global indicator that characterizes the technical dimension of WEN, and can be used to substantiate decisions on improving energy efficiency and reducing negative environmental effects.

New studies are required to be developed also on the demand side, to take into account the social and environmental constrains.

Transdisciplinary approach could be applied in deeper understanding and managing WEN linkages. This approach, which incorporates a wide range of scientific, technic, social and political issues, including various actors, could give solutions to complex problems for achieving the goals of sustainable development.

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