Water-energy nexus in regional model instances: a focus on the Piedmont residential sector

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Water-energy nexus in regional model instances: a focus on the Piedmont residential sector#

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ABSTRACT
Realization of carbon neutrality and net zero emission policies require a detailed vision of the target energy systems and accurate planification of the transition paths. Open-Source Energy System Optimization Models (ESOMs) are consolidated tools used to back policy makers and stakeholders to examine technological and economic requirements of such goals. Nevertheless, the restriction of these tools to only-energy commodities represent a significant drawback of such models since they may lead to overlooking impact of the actions on resources with other natures. In addition, it is essential to evaluate the feasibility of the policies considering the availability restrictions and limits of other resources. Water is one of the commodities that is highly tight with energy systems, whether directly or indirectly. This paper presents a methodology for water-energy nexus implementation within the upstream and residential sectors of the TEMOA-Piedmont open-source ESOM.

Keywords: Water-Energy Nexus, Energy transition and sustainability, Open-source Energy System Optimization Model, TEMOA-Piedmont, Regional Water-Energy Nexus Model.

NOMENCLATURE

Abbreviations	
ESOM	Energy System Optimization Model
RES	Reference Energy System
RWS	Reference Water System
Symbols	
kWh	Kilowatt hours
PJ	Peta joules
Mm^3	Millions of cubic meters
GW	Giga Watts

1. INTRODUCTION

The interconnectivity of water and energy has not just bidirectional complexities but also extends to the numerous sectors and appliances in which the two commodities meet [1]. From the first steps of generation and supply, water and energy start to serve each other in different technologies and fields [2]. This reciprocates relationship continues until the last phases of each commodity. Lots of energy final demands, independent from the activity sector, need the presence of water and the same holds for final water demands [3].

Nowadays, a substantial part of research and policies address solutions for decarbonization and emission reduction strategies. Success of these solutions depends on careful study and analysis of the targeted zone, sector or activity. Energy System Optimization Models (ESOMs) are among the most important tools in this regard. ESOMs rely on a bottom-up structure, backed by a rich technological inventory characterized by different techno-economic factors [4]. These frameworks determine the cost-optimal technological configuration while meeting the final demand, according to the desired scenario [5]. Moreover, ESOMs enable long-term monitoring of the activity sectors of their Reference Energy System (RES) which can vary from global to sub-national and regional levels [6]. In addition, ESOM’s boundary, defined throughout RES, can be kept as a single region or be divided into several spatial regions [4].

Although the integrated Water-Energy modelling is not common practice, recent water scarcity, droughts, extreme climate events and awareness about sustainable strategies brought the necessity of more comprehensive analysis into the attention of academics and policymakers [7].

Notwithstanding their potential, ESOMs have traditionally been limited to modeling the supply and demand dynamics of energy commodities, from upstream production and generation to end-use

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consumption. This limitation can lead to over-or-understanding technologies capacity expansion or activity levels, as the availability of other essential resources is not considered. Moreover, these models fail to give an insight into the impacts that energy policies may have on the consumption of other resources, affecting thus the sustainability of such plans [8]. Because of the extension of their sectors and variety of their technologies, nexus implementation in ESOMs has the benefit of enabling a vast nexus analysis in various activity sectors and different technologies. Furthermore, regional models capture more accurately the zonal features of the coupled resources, especially in the case of water [9] allowing for a better representation of availability of other local resources and their management, distribution constraints, and usage patterns in connection with energy resources.

Nevertheless, there are important barriers related to data availability and its reliability to overcome [10]. Indeed, to evaluate the reliability of the data used to develop the present study, different interviews with the regional water authorities was performed [11]. In recent years and thanks to smart metering techniques this gap is getting less relevant [12]. Another influencing factor is the nature of water resources. Unlike energy, defining a control volume for a water system requires accounting for phenomenon of various mechanisms such as rainfall, evaporation, infiltration and eventually presence of not registered supply methods such as wells [13].

The present study aims at filling the gap of energy transition planning and water-nexus analysis by deepening the water-energy nexus implementation methodology within the upstream and residential sectors of an ESOM. The methodology already presented and tested for a simplified case in [13], has been extended and explored within a more articulated model. The case studied is the Piedmont energy system model developed in the Open-source TEMOA framework [14]. The TEMOA-Piedmont [15] model, among the first regional TEMOA instances, is the first ESOM of the Piedmont Region and is introduced in [6]. The time horizon of the model spans from 2011 to 2050, with 2021 the last calibrated year of the model.

2. MATERIALS AND METHODS

The very first step for implementing the nexus typically concerns the development of the structure of the Reference Water System (RWS). RWS defines water supply and demand sides and, like RES, depends on the model's target region and base year. Due to the rarity of the water-energy nexus practices, the determination and development of an RWS structure from scratch are typically necessary. RWS contains all the technologies related to the water sector regardless of their possible energy consumption. Once RWS is defined, it is then necessary to establish the connection points between RES and RWS. These connection points, distributed in almost all sectors, are indeed technologies where water and energy are consumed simultaneously (see the example of residential sector technologies in Fig. 1). In addition to technologies, identifying the type of consumed energy-commodities is necessary as well. RWS-RES linkages need to be established by proper technical parameters for the identified technologies, including the technology *"efficiency"*. For a generic technology t with i inputs and j outputs, the *"efficiency"* can be calculated by Eq. 1. It is important noting that the value obtained in such a way is not dimensionless as it determines the quantity of the output commodities with respect to the input ones, considering their respective units of measure.

$$\eta = \frac{\sum_j Flow\_Out_{t,j}}{\sum_i Flow\_In_{t,i}} \qquad 1$$

Other important couple of parameters to define the connection are *"TechInputSplit"* and *"TechOutputSplit"*. The former, calculated for the technology k as shown in Eq. 2, establishes the minimum share of each input and is used to regulate the quantity of an input in relation to others. Similarly, *"TechOutputSplit"* is used to regulate the quantity of an output commodity in relation to the others and is calculated like *"TechInputSplit".*

$$TechInputSplit_{t,k} \leq \frac{Flow\_In_{t,k}}{\sum_i Flow\_In_{t,i}} \qquad 2$$

Finally, when the capacity and activity of a technology are expressed in different units, also the *"CapacityToActivity"* factors need to be adjusted properly. This parameter determines the relationship between the capacity of a technology and its activity, in case they have two different measurement units. An example is represented by power plants, with the capacity expressed in power (e.g., GW) and activity in energy (e.g., TWh or PJ) units.

2.1 Water-energy nexus implementation in TEMOA-Piedmont optimization model

In the presented case study, the most important energy vector to establish the connection of the energy and water modules of the model is electricity. In the actual state of the model, it is the only energy vector upstream while other commodities are present in the water heating and cooking services of the residential sector.

2.1.1 Upstream

The structure of the water upstream in the model's base-year, 2011, was determined using data related to the water concession types and the authorized withdrawals in Piedmont [16]. The concessions are regulated by the "Regional Regulation. 10/R" of 29 July 2003 [17] and include categories slightly different from the energy module sectors. To be coherent with the energy module, the categories were revised as reported in the first column of Tab. 1.

Tab. 1. Water use sector, withdrawals and the final demands in the base year of the model 2011.

Uses	Withdrawals (Mm^3)	Demands (Mm^3)
Agriculture	3.03E+02	3.03E+02
Drinking	6.02E+02	3.22E+02
Commercial	7.14E+00	7.14E+00
Energy	7.03E+03	7.03E+03
Industry	7.46E+01	7.46E+01
Total	**8.01E+03**	**7.73E+03**

According to statistics of the "Water Protection and Sustainable Use" direction of Piedmont Region's Web-Meters [18], the water supply resources of the Region include rivers, natural and artificial lakes and ponds, springs and wells.

The total water withdrawal, 8010 Mm^3, was assigned to the model sectors in the base year. The water uses, along with their respective withdrawal volumes and final demands for 2011 are reported in Tab. 1. The transport sector, present in the energy module, was assumed to have no water uses.

The drinking part of the water denotes the freshwater which enters the water potabilization technology. This technology still belongs to the upstream of the model and is one of the connection points of energy and water module due to energy consuming processes. This technology was absent in the energy module and needed to be characterized.

The statistics relative to the withdrawal drinking water volumes were taken from the annual reports of the Integrated Water Services Observatory (Servizio Idrico Integrato, SII in Italian) [19] starting from 2015. According to these reports, almost 60% of the Region's drinking water is supplied from wells while the rest is approximately equally taken from surface water bodies and springs. The dominant use of wells for drinking purposes is because of the higher quality and lower contamination of groundwater resources.

To determine the electricity consumption of the water treatment technology, data by SMAT® [20], the biggest water supplier company of the region, serving 52% of the Region's inhabitants, was used and was assumed to be representative of the region. The company activities included withdrawal, accumulation, lifting, potabilization, distribution and services, consuming overall 0.8 PJ of electricity. Water collection, purification and distribution required a total of 0.5 PJ, the remaining 0.3 PJ was related to wastewater facilities and services.

Using the shares of each activity from the total consumed electricity by [20], the company's electricity consumption due to water process (0.5 PJ) was disaggregated among the activities. Not being a process, the item "services" was excluded. For the SMAT®'s activities and respective energy use shares see the two first columns of the upper part of Tab. 2.

Tab. 2. Water treatment facility's characterization parameters.

Service	Shares in 2011 (%)	Electricity consumption (PJ)
Withdrawals	49.9	2.50E-01
Accumulation and lifting	41.0	2.05E-01
Potabilization	6.9	3.45E-02
Distribution	1.1	5.50E-03
Services	1.1	5.50E-03
Service	**Referred volumes (Mm^3)**	**Specific energy (PJ/Mm^3)**
Withdrawals	238.49	1.046E-03
Accumulation and lifting	243.60	8.415E-04
Potabilization	243.60	1.416E-04
Distribution	243.60	2.258E-05

In 2011, the total water treated by SMAT® was 238.49 Mm^3 while 243.60 Mm^3 were supplied [20]. The 3 % difference stemmed from the external supplies. Using these volumes and the consumed electricity obtained previously and reported in the third column of Tab. 2, the specific energy per service type was calculated and can be seen in the third column of the lower part of the same table.

The unique technology in the model representing the water treatment facilities includes *withdrawal*, *accumulation and lifting* and *potabilization* services and is assumed to have 2.03E-3 PJ/Mm^3 specific consumption, the sum of the specific energies of the mentioned activities (see the last three rows of Tab. 3). The "*distribution*" energy consumption is allocated to another technology representing the pipeline network (reported in the last row of Tab. 3).

Knowing the specific energy and the total drinking water withdrawal of the Region in 2011, 602 Mm^3, the consumed electricity in treatment technology of the model was calculated. Because of the lack of data, no water lose is assumed in this technology.

As the input and output commodities of the water treatment technology were determined, using Eq. 1 the pseudo-efficiency of the plant, amounting to 0.998 $Mm^3/(PJ+Mm^3)$ was calculated.

2.1.2 Water pipelines

One of the biggest issues of the water supply system in Europe and Italy is the aged water distribution system [3]. In 2012, the average efficiency of the Italian water pipeline was 63% while it was 62% in Piedmont [21].

According to the Italian Statistics Institute (ISTAT) [22], all fractions of Piedmont are served with water pipelines thus, the total volume of *drinking water* was assumed to enter the distribution system and 40% leaks through the water distribution system.

Tab. 3. Final energy consumption of water treatment and distribution technologies in the base year of the TEMOA-Piedmont-WE model.

Service	Final Energy per Service (PJ)
Withdrawals	0.64
Accumulation and lifting	0.51
Potabilization	0.09
Distribution	0.014

The specific electricity consumption previously calculated (i.e., 2.26E-05 PJ/Mm^3) and the water volumes are used to determine the total energy used in the technology presenting the distribution service amounting to 1.37E-02 PJ. The specific and total energy consumptions of the distribution technology are respectively visible in Tab. 2 and Tab. 3.

Assuming 40% of losses, a volume of 358 Mm^3 reaches the end users. These parameters were used to calculate the efficiency of the technology presenting the water pipelines, 0.594 $Mm^3/(PJ+Mm^3)$.

2.1.3 Residential water

A schematic representation of the technologies present in the residential sector of the integrated model is presented in Fig. 1. As previously mentioned, water is assigned to all demand side sectors of the model except for transport. The drinking water disaggregation factors were adopted extending the 2011 shares announced by SMAT® [20] for the whole region. As outlined by SMAT® [20], 77% of the total drinking water supplied by this company was consumed in the residential sector. This share results in 275 Mm^3 of assigned potable water to the residential sector. It is important to note that, in addition to drinking water, also a raw water commodity is assigned to other sectors.

To allocate the residential water to the final uses, it was needed to split it into hot and cold water. According to a study performed for the household water usages in Australia and New Zealand [23], 30% of drinking water is consumed heated while the resting 70% as cold water. Consequently, the residential water intended to be heated is 82.6 Mm^3 while 192.8 Mm^3 as cold water.

Water heating technologies are among the connection points between energy and water modules.

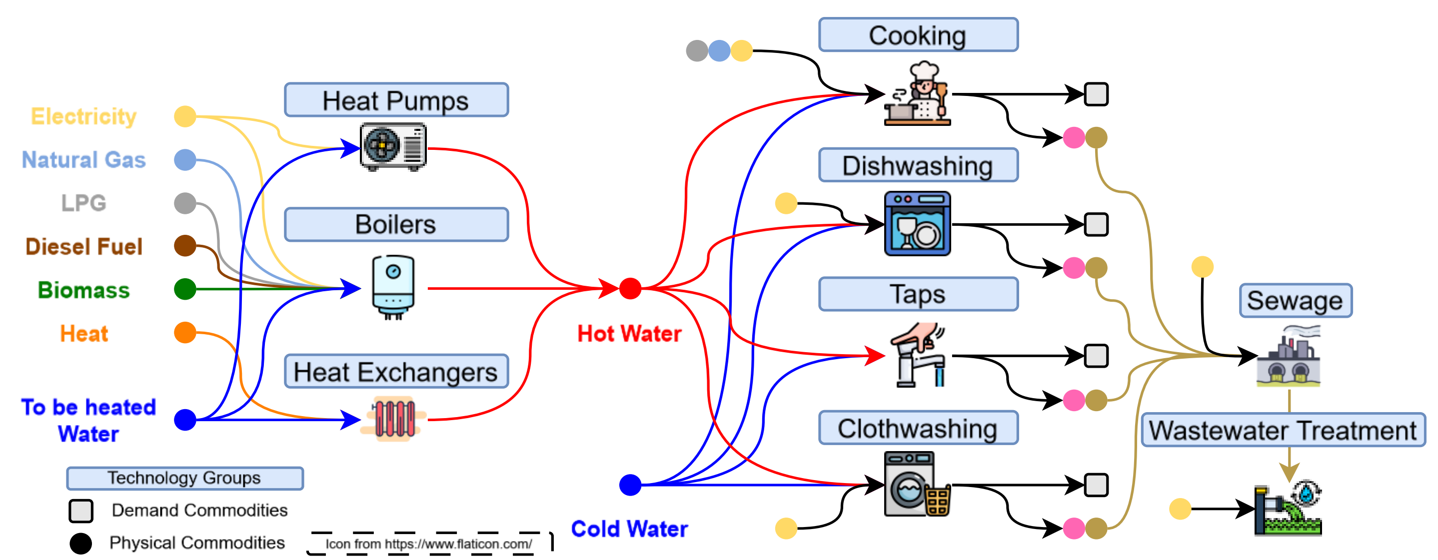

Fig. 1. Scheme of the TEMOA-Piedmont residential sector, highlighting energy and water items.

As explained before; to establish the connections, it is necessary to adjust technical parameters of the existing and new technologies adequately.

The volume of the to-be-heated water was distributed among the existing water heating technologies using the shares of their final energy commodities over the sum of all final energies used in water heating service. In case of the TEMOA-Piedmont the commodities to meet this service are natural gas, electricity, diesel fuel, heavy fuel oil, LPG, biomass and heat. The disaggregation factor to assign water to the natural gas boiler is 5.45/11.5=0.474 resulting in 39.2 Mm^3 to be assigned to this technology.

Water heating service is assumed to have no physical water losses, so the input water volume equals the output one. Moreover, besides the energy service demand, the water heating technologies are configured to have two water output commodities, one defined as a demand, while the other, equal to the previous one, flows further into the model to be consumed as hot water commodity in final uses (see Tab. 4).

Tab. 4. Input and output commodities of the new natural gas fueled technologies the model.

Inputs		Outputs	
Natural Gas	1.00 PJ	Heated Water (Energy Commodity)	0.92 PJ
Water	12.3 Mm^3	Heated Water (Water Commodity)	12.3 Mm^3

To characterize the new technologies of the water heating service, the specific water uses in Mm^3/PJ of each heating technology types (divided based on consumed fuel) was calculated. For the natural gas boilers, it is 39.2/5.45=7.2 Mm^3/PJ.

Assuming again no water loses also in the new technologies, the input and output water volumes will be equal. To calculate the useful energy, which is the technology output, the unitary final energy is multiplied by the technology's energy efficiency. Once all the entering and exiting commodities are known, the efficiency can be calculated using Eq. 1. After being heated, hot water flows further into other technologies of the residential sector which may or may not consume energy to meet other service demands (see Fig. 1).

The residential sector water end-uses and their respective hot and cold water shares adopted from [23] can be seen in Tab. 5. The end-uses include *shower*, *bath*, *cloth* and *dish washers*, *toilets (flush tank)* and *taps* where taps incorporate *cooking, bathroom* and *laundry.* Because the tap water included several services, it was needed to be further disaggregated. Thus, 50% of it was assigned to cooking purposes. Among the indoor water end uses, dishwashing, cloth washing and cooking form other connection points between water and energy modules.

Once the hot and cold water inputs were determined, characterization of cooking, dishwashing, and clothes-washing technologies followed the same procedure used for water-heating technologies: in case of the existing technologies, the water was distributed among different fuels based on the share of the final energy of their consumed fuel in total final energies of that specific service.

Tab. 5. Household water end uses, and relative shares [23] used to disaggregate water types by end-uses.

Indoor water uses breakdown						
Water type	**Taps**	**Shower**	**Bath**	**Clothes Washer**	**Dish Washer**	**Toilet**
Hot	22%	51%	9%	17%	1%	
Cold	9%	20%	3%	29%	2%	37%

These technologies were assumed to have 10% of difference between input and output of water commodities, representing the portion of water which is consumed and does not return into the system because of being absorbed in cooking or by the clothes etc.

Once again here two water commodities are assumed to leave the technology. One to determine the services' water demand and the other to present the wastewater flowing further to the technology presenting sewer lines and ending in wastewater treatment plant.

Regarding the technologies without energy consumption, such as taps, the efficiency is determined considering just the water commodities in input and output, with outputs loosing 10%. As previously explained, also these technologies have two quantitatively equal water commodities in output. One to determine the demand of that end-use and the other to flow further into the sewer system and end in the wastewater treatment plants.

3. SCENARIOS AND RESULTS

This section presents the investigated scenarios and the associated results. Three explored scenarios consider different assumptions (lower limit, baseline and upper limit) on the future evolution of the Piedmont population which is the allocated driver to both energy and water final service demands in the residential sector of TEMOA-Piedmont [24]. Such trends correspond to projections taken from ISTAT reported by the Region [25] and foresee a decreasing population up to 2050 in the baseline scenario, with approximately ±9% compared to baseline for the “upper limit” and the “lower limit” scenarios. It is worth noting that, as with energy resources, scenarios relative to water resource constraints (representing droughts…) can also be implemented into energy system models by limiting the maximum activity and capacity of primary water sources. Indeed, in the present case, to regulate the water resources maximum capacities, reflecting existing water use concessions are applied.

As shown in Fig. 2, final energy consumption shows a slight increase over time, driven by the evolution of other final demand drivers [6]. Across all years, natural gas remains the most consumed energy carrier, followed by oil products and electricity. Sector-wise, the residential sector is the highest energy consumer, given the climatic conditions in the region. The transport and industrial sectors follow in terms of total energy consumption. The overall structure of consumption by fuel and sector remains relatively stable over time.

Water consumption in residential end-uses (see Fig. 3) mirrors the trends seen in energy use with only minor variation across scenarios. A ±9% change in population leads to an approximate ±4% change in water consumption by 2050, compared to the baseline (Fig. 3). The relative share of water use across the different residential services does not vary significantly between scenarios, as shifts in population affect overall consumption levels but not the distribution across end-uses.

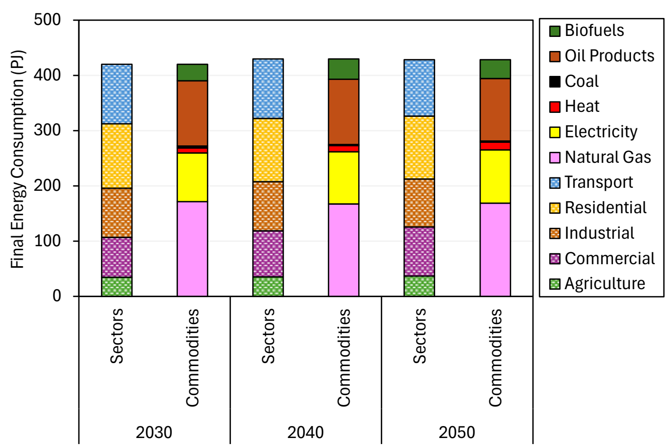

Fig. 2. Final energy consumption evolution by end-use sectors (left columns) and energy commodities (right columns) in the median scenario.

Fig. 4 illustrates both the total final energy consumption of residential appliances that link the energy and water modules and the deviation from the baseline scenario under population variations. The population change of ±9% by 2050 corresponds to an approximate ±4% change in energy consumption (Fig. 4).

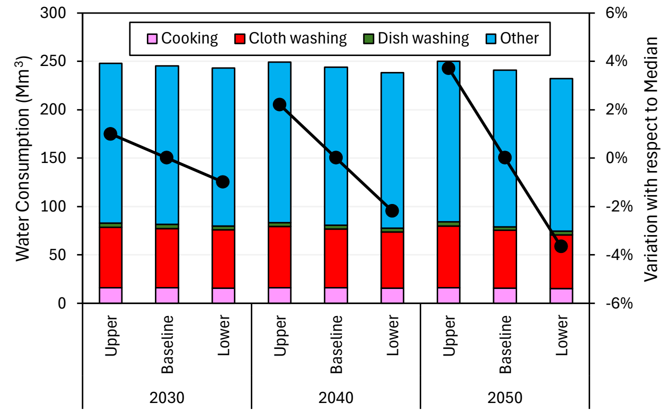

Fig. 3. Water consumptions in the residential final services in the three scenarios (left-axis) and their variation with respect to baseline (right-axis).

Fig. 4. Final energy consumption evolution in the residential appliances used to connect energy and water module (left-axis) and their variation with respect to baseline (right-axis). The energy consumption does not include the energy input of boilers for water heating.

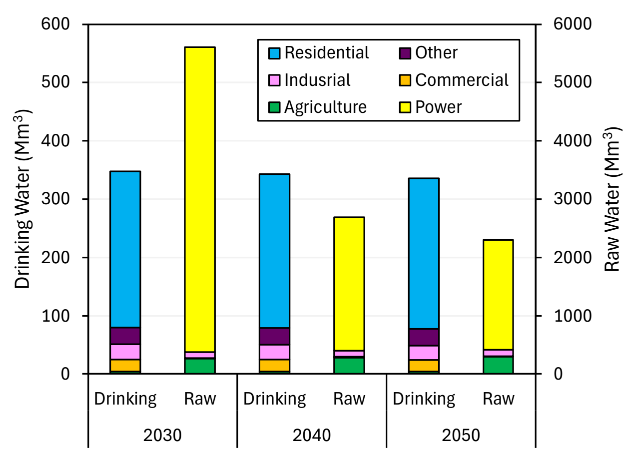

Fig. 5. Final drinking and raw water use by sectors in the median scenario of the model.

Cooking remains the most energy-intensive service among the considered end-uses. Despite the variation in total values, the relative shares of different end-uses remain largely consistent across scenarios, indicating a stable structure in residential energy use.
Eventually, as shown in Fig. 5 and for the median scenario, drinking water use is dominated by the residential sector, which consistently accounts for most of the consumption throughout the time horizon. Sectoral shares remain relatively unchanged. In contrast, raw water use is primarily driven by the power sector, particularly by hydropower generation, which is highly water-intensive. As the share of hydropower in the electricity mix decreases over time, the total raw water consumption also declines. Agriculture ranks second in raw water use but remains relatively stable compared to the notable drop in the power sector's demand.

4. DISCUSSION AND CONCLUSION

A full understanding of energy transition requires the development of instruments able to assess the interconnection of water and energy resources and study the impact of the future scenarios on both systems. This work presented a methodology of the water-energy integration implementation within an ESOM. Nevertheless, being among the first attempts, there are some limitations which need to be taken into consideration. Indeed, the water consumption disaggregation refers to the Australian patterns which may differ from the European and more specifically the Italian way of consumption. In addition, as the technology inventory of RWS is not diversified and in major cases contains just one technology, the optimization is performed just among the energy sector technologies. Including different technologies and consequently, different costs could give also a wider perspective over the economic aspects of water technologies. The methodology adopted for water-energy integration is broadly applicable to various case studies. Nevertheless, because of the characteristics of water-resources, the specific water and water/energy consumptions of different technologies and appliances require adequate modifications. As integrated water-energy tools such as the present model are not yet widely adopted, it is essential to promote their capabilities to regional authorities. To this end, several meetings have already been planned with local stakeholders to present the model's potential and encourage its application in decision-making processes.

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