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Development of a decentralized innovative brackish water treatment unit for the production of drinking water

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ABSTRACT

Access to water constitutes a necessary condition in order to ensure life. This paper deals with the development of an innovative energy autonomous system in order to provide drinking water in isolated small communities, using brackish water as feedstock. The case study is a small village in Jordan, where the system that was designed and constructed in Greece, was installed. The unique characteristic of the innovative system is its compact form that incorporates the reverse osmosis unit and the renewable energy production from three sources, wind, solar and water. The energy autonomous system for the production of drinking water from brackish water can be used as a decentralized unit for isolated areas where access to clean water and electricity is not available.

Keywords: Brackish water; Drinking water; Small communities; Energy autonomous; Renewable energy sources; Jordan

1. Introduction

In December 2010, the United Nations General Assembly declared 2013 as the United Nations International Year of Water Cooperation. UN recognizes that cooperation is essential to strike a balance between the different needs and priorities and share this precious resource equitably. It is noted that today 783 million people still remain without access to an improved water supply. Many more use water that is unsafe to drink [1].

Although the absolute quantities of freshwater on Earth have always remained approximately the same, the uneven distribution of water and human settlement continue to create growing problems in freshwater availability and accessibility. Seawater and brackish water desalination have been proven to be technologically sound and promising options for combating water crisis.

For the case of Jordan, water demand constitutes a serious challenge to future economic growth, due to environmental and social factors, such as the arid climate, the minimal rainfall, the high percentage of evaporation, the small groundwater contribution to

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the total water supply, the increase of the human population, as well as the agricultural expansion.

The growing population and the climatic and topographical conditions in Jordan have caused significant pressure on the limited water resources, as well as severe water supply-demand imbalance. At the same time, the use of renewable water resources remains rather low. Jordan is among the four poorest countries in the world in terms of water resources and falls below the water poverty line (1,000 m^3/capita/y). In the year 2008 the renewable freshwater resources available per capita in Jordan were about 140 m^3/capita/y. By the year of 2025, the available per capita per year will be 90 m^3, an estimation that categorizes Jordan as a country with absolute water shortage. The per capita of water supply in Syria and Iraq reach 1,028 and 2,172 m^3, respectively. This shows the extent of water poverty in Jordan in comparison with the neighbouring countries. The supply-demand imbalance has influenced the quality of water resources; over abstraction from groundwater aquifers has exploited the aquifers at more than double their sustainable yield in the average. Due to the population growth and the increasing living standards in urban areas, it is expected that the total water demand will rise to 1,647 Million Cubic Metres (MCM)/year in 2020, compared to 1,321 MCM/year in 2005. The Ministry of Water and Irrigation plans to partly satisfy the rising demand by increasing wastewater reuse [2]. On the basis of 2010 data, the agricultural sector was the major consumer of freshwater, as presented in Table 1. Since domestic water use constitutes the main priority in Jordan, the share used for agricultural purposes is expected to decrease in the future [3].

The main water consumers in Jordan are summarized in Table 1 according to data referring to the year 2010.

The gap between supply and demand was actually solved by the unsustainable practice of overdrawing highland aquifers, leading to lowered water tables and declining water quality [4]. The water deficit in the country is usually addressed by reducing and rationalizing the water use by the domestic and the agricultural sector. In many areas the potable water supply is delivered to the households once a week. The deficit gap tends to expand as a result of continuous increase in population, increase in economic (agricultural, industrial and other sectors) growth and tourism.

Table 1
Use of water in Jordan

Users	Percentage (%)
Agriculture	64
Domestic	30
Industrial	5
Tourism	1

Considering the difficulties for the water sector in Jordan, it is crucial to develop new water resources and to find ways to increase the water supply.

The national non-conventional water resources include use of treated wastewater, treated greywater, water harvesting, desalination of brackish groundwater and seawater [5–7]. Treated wastewater and greywater are used in Jordan for irrigation and are considered as valuable sources [8]. However, brackish water wells have not yet been used for any purpose.

Desalination of brackish water in Jordan can be more convenient and realistic in the short term than seawater desalination. Jordan has considerable brackish water resources [9]; thus, desalination of brackish water can be a valuable source of water for domestic use.

The high energy requirement of large-scale desalination and lack of expertise in the field of desalination constitute main future challenges for promoting the desalination of brackish water in Jordan [10].

Until now, the desalination potential of either seawater or brackish water has been very limited in the country. Some small-scale brackish water desalination is applied in the Jordan Valley. About twenty stations provide water mainly for irrigation and commercial/industrial purposes. These stations are owned by the private sector and are located north of the Dead Sea [11].

Since Jordan has few fossil fuel sources of its own, it seems to be more financially feasible to combine brackish water desalination with renewable energy sources. Such a concept is especially promising for the cases of small decentralized systems covering the needs of local communities [12].

The electricity consumption in Reverse Osmosis (RO) plants depends on the feedwater quality. The electric energy consumption per m^3 of water ranges for the case of seawater between 4 and 7 kWh/m^3 and for brackish water from 1 to 3 kWh/m^3.

The groundwater basins in Jordan are summarized in Fig. 1.

Currently, Jordan produces about 50 Million Cubic Meters (by desalination from over 10 desalination plants (the majority of which comprise RO plants) (Table 2), out of which 40 MCM are being used for domestic purposes and 10 MCM for irrigation. Table 2 summarizes the data about the existing desalination units in Jordan, while Table 3 outlines the sources of brackish water that can be utilized.

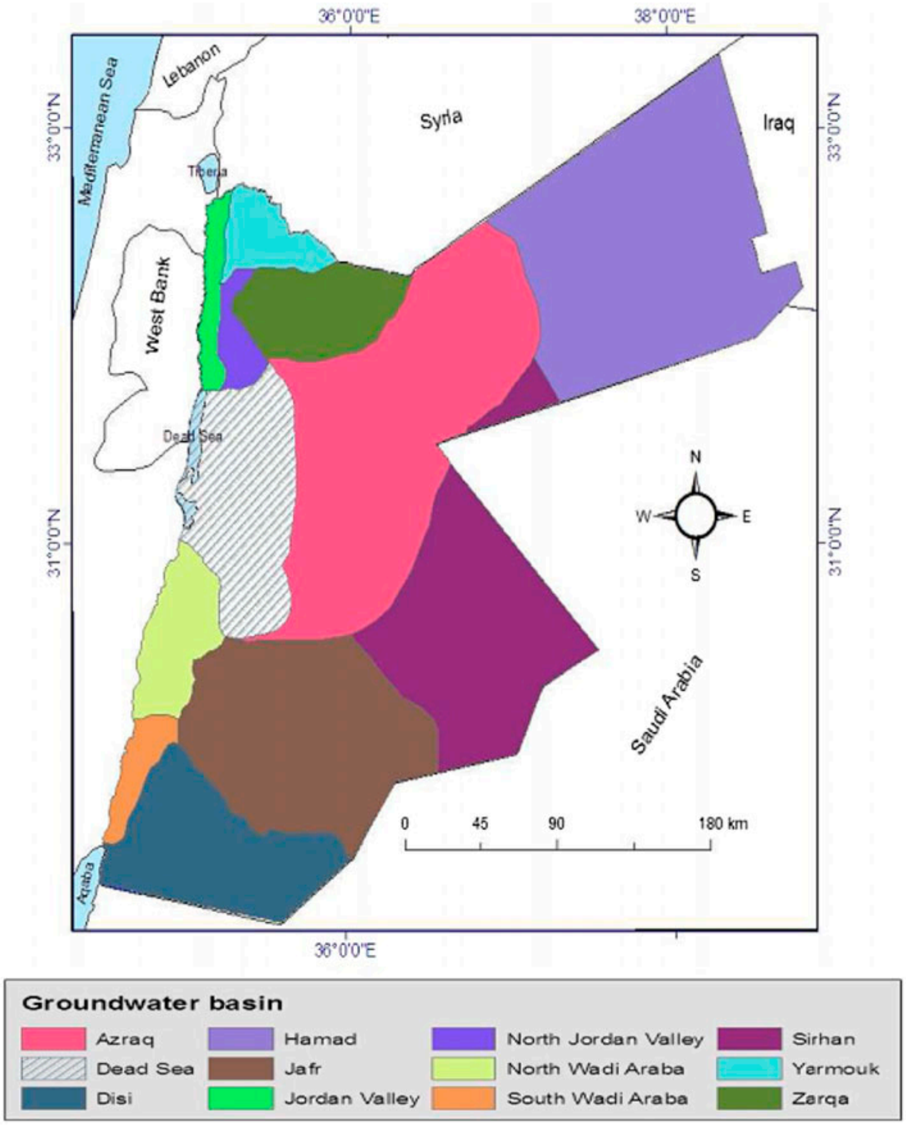

Fig. 1. Groundwater basins in Jordan.

In Jordan, there is not only a water shortage problem, but also electricity is mainly produced using fossil fuels and in some cases there is a lack of electricity grid connection. Renewable energy driven desalination has been evaluated by different researchers as the most suitable option resulting from multi-criteria analysis under economic, technical, availability, reliability and environmental sustainability criteria [15–20].

2. The innovative system for the treatment of brackish water

Based on the aforementioned existing situation in Jordan, and the fact that the decentralised concept of brackish water desalination system using renewable energy source should be further explored, an energy autonomous unit has been developed for this purpose. The methodology used to develop, install and operate the innovative system, so as to achieve the production of drinking water starting from the available brackish water, included the following steps:

- Analysis of the current situation regarding the management of water resources in Jordan.
- Presentation and analysis of the current situation regarding the management of brackish water in Jordan.

Table 2
Information about desalination units operating in Jordan [13]

Location	Total capacity (m^3 d)	Unit	Process	Water quality	Construction year
Amman	360	1	RO	Brackish	1979
Amman	3,028	4	RO	Sea	1981
Amman	1,200	1	RO	Brackish	1981
Amman	409	1	RO	Brackish	1981
	719	1	ED	Brackish	1982
Irbid	545	2	RO	Sea	1982
	1,584	2	RO	Brackish	1983
Azraq	600	1	RO	River	1987
Aqaba	1,100	1	VC	Sea	1997
	818	1	ED	Brackish	1998
	800	2	RO	Sea	2001
Aqaba	1	1	THE	Sea	1987
Hisban	4	1	RO	River	2001
TOTAL	11,168	19	–	–	–

Table 3
Sources of brackish water which can be utilized from different groundwater basins [14]

Ground water Basin	Aquifer	Storage amount of nonrenewable (billion m^3)	Assumed safe yield of renewable (MCM/a)	Salinity (TDS) (mg/l)
Azraq	A7/B (north to central)	46		1.000–2.500
	A7/B2 (south)		10–12	1.000–1.700
	Kurnub	42		1.350–3.000
Jordan valley	A11		6	1.350–2.500
Dead sea	A7/B2		9–12	1.000–1.700
Wadi Araba	A1 (north to south)		8	1.000–7.000
Jafr	A7/B2	1.7		1.000–4.000
	Kurnub	12		1.400–3.000
	Khreim	88		1.200 to >10.000
Sirhan	B4		5	1.000–2.500
	A2/B2	32		4.500–7.000
Hammad	B4/B5		7	1.000–3.000
	A7/B2	16		1.500–3.200
Total	–	237.7	55–60	–

- Study and design of the prototype, autonomous energy, integrated pilot system for treating brackish water.
- Construction and installation of the pilot system for the treatment of brackish water.
- Operation of the pilot system.
- Evaluation of the pilot operation and optimization of the system performance.

On the basis of the data of the primary steps, the developed innovative system includes the following main components:

- RO membrane unit
- Photovoltaic system (PV)
- Wind turbine system
- Vertical pulsatory motion of a conductor within water (patented system)
- Storage water tanks
- Batteries

The main parts of the developed system can be summarized and seen in Fig. 2.

The innovative decentralized system, which was constructed in Larisa, Greece and installed in Jordan, uses a hybrid system for the production of drinking water from brackish and saline water. The hybrid energy autonomous system uses solely renewable energy from three sources, namely:

- the wind with the use of a vertical axis rotor,
- the sunlight through the use of photovoltaic panels,

- the energy production from water under pressure through the pulsatory motion of a conductor inside a magnetic field.

The hybrid system has the capability to produce and store electricity up to 25 kW, utilizing the three types of renewable energy sources.

The wind part of the hybrid system uses the specially designed vertical axis rotor, up to 10 kW. Its nominal capacity is 10 kW, while the design involves vertical axis, four curved shape blades. The mechanical energy produced from the rotation of the blades is converted (after speed change with a gear box) to electricity. This conversion is realized through the use of energy converters and the energy produced is stored to the batteries system which is installed in the underground support metallic base. Different views of the wind power system are provided below (Fig. 3).

The solar part of the hybrid system uses photovoltaic (solar) cells up to 2 kW. The nominal capacity is 2 kW, the design involves single-crystalline silicon, while mounting is under the rotor, on the main body (eight photovoltaic panels). The slope of the support bases and the connection of photovoltaic panels ensure maximum output per surface. The power produced from the solar system is stored to the batteries system which is installed in the underground support metallic base.

The third part of the renewable energy of the hybrid system originates from the vertical pulsatory

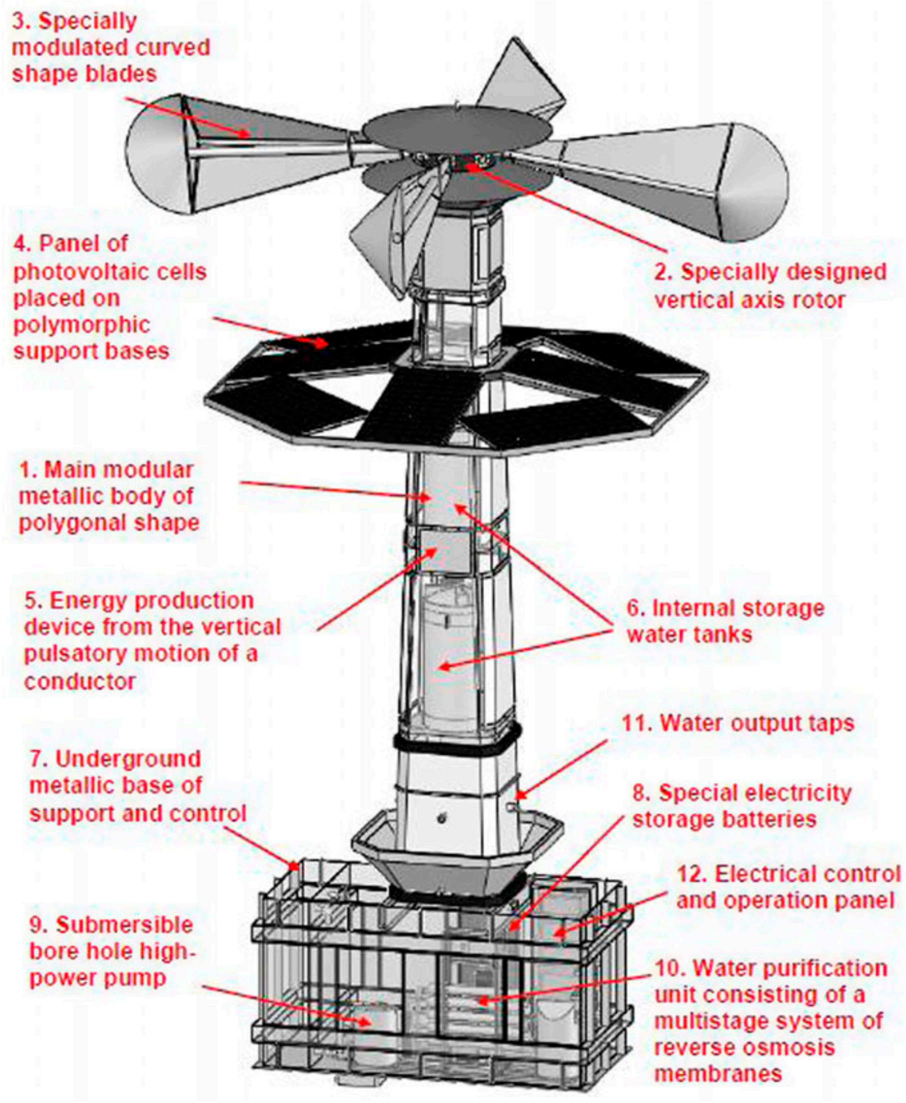

Fig. 2. Different components of the developed system for the production of drinking water.

Fig. 3. Different views of the wind power system.

motion of a conductor inside a magnetic field (natural magnet), inside a liquid layer of water under pressure, up to 13 kW. This renewable energy is provided by a patented system (Patent No. 1006179) of the Greek Company Soukos Robots. Its nominal capacity is 13 kW and it is noted that this unique power generation system has introduced an additional innovation to the overall system providing an exceptional advantage in relation to other conventional renewable power systems.

Fig. 4. RO subsystem.

Water purification is achieved through the operation of the RO membrane unit (Fig. 4). Its main characteristics are summarized in Table 4. This subsystem has a pretreatment stage, the main treatment stage and thee post treatment stage.

The pretreatment stage of the RO subsystem includes:

- Pre-chlorination dosimeter (sodium hypochlorite solution for the oxidation and removal of soluble iron and manganese of the brackish water). It includes a 200 lt polyethylene (PE) tank with a dosing pump (stainless steel (316 LSS) feeding pump for feeding the system, required flow rate: 3.0 m^3/hr, Operating pressure: 4.4 bar, Motor: 1.0 kW, IP 55, 380 V.
- Multi-layer sand pyrolusite filter (removal of suspended particles and iron ions) (Maximum operating pressure: 10 bar, Shell material: FRP with PE lined, Valves: five (5) independent automatic pneumatic, with pneumatic, actuator (VM1, VM2, VM3, VM4, VM5), Filling materials: quartz sand of different grain sizes and pyrolusite.

- Multi-layer activated carbon filter (removal of free chlorine and residual iron) (Maximum operating pressure: 10 bar, Shell material: FRP with PE lined, Valves: five (5) independent ball valves manual PVC, PN 16, Fillers: quartz sand of different grain size and active carbon).

The treatment stage of the RO subsystem involves:

- Stainless steel high-pressure pump (Required rate: 2 m^3/h, Operating pressure: 8-10 bar, Motor: 2.2 kW, IP55, 380 V, 50 Hz). The high pressure pump has been selected for operating pressure for at least 4 bar higher than the theoretically predicted for the particular quality of raw water.
- Six (6) RO membranes.
- Pressure vessels containing the membranes:
  - Three vessels (two membranes per vessel).
  - Maximum pressure: 21 bar.
  - Side entry for easy-opening inspection.

Table 4
Technical characteristics of the RO subsystem

Brackish water treatment system	
Reverse osmosis capacity	1.7 m^3/h (40 m^3/d)
Recovery rate	65%
Feed pressure	6-12 bar
Feed water temperature	10-60°C
Dosage of antiscalant	6 ppm (gr/m^3)

Fig. 5. Indicative view of the RO system including the brackish water pipeline entrance to the main system.

Fig. 6. Close view of the drinking water storage tanks.

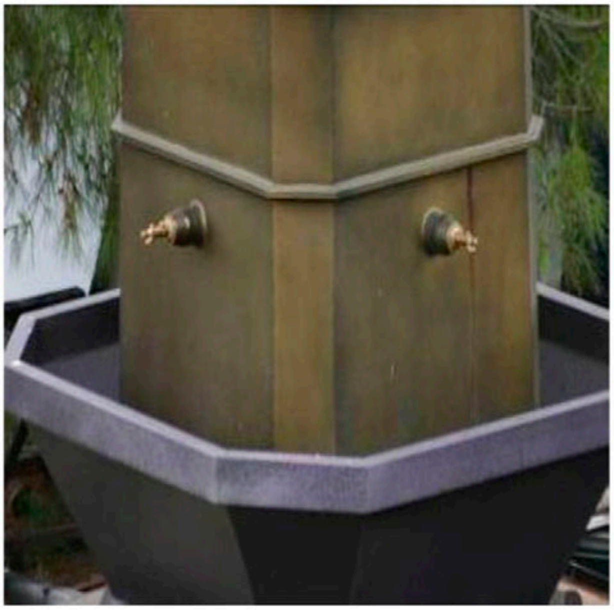

Fig. 7. Water output taps.

The post-treatment (permeate rehardening) stage of the RO subsystem includes:

- Ultraviolet radiation (UV) device for the disinfection of remixing current (filtered feeding water). The UV unit is stainless steel with a capacity of 1.8 m^3/h.
- Dosimeter feeding system of sodium hypochlorite solution (chlorine) for the protection of stored distributed water from micro-organisms. It includes 200 L PE tank with dosing pump.

The brackish water enters the system through a pipeline (Fig. 5) and is conveyed to the main treatment system for its conversion to drinking water. After treatment, the clean water is injected automatically to the two (2) drinkable water storage tanks (Fig. 6), placed along the main body of the system.

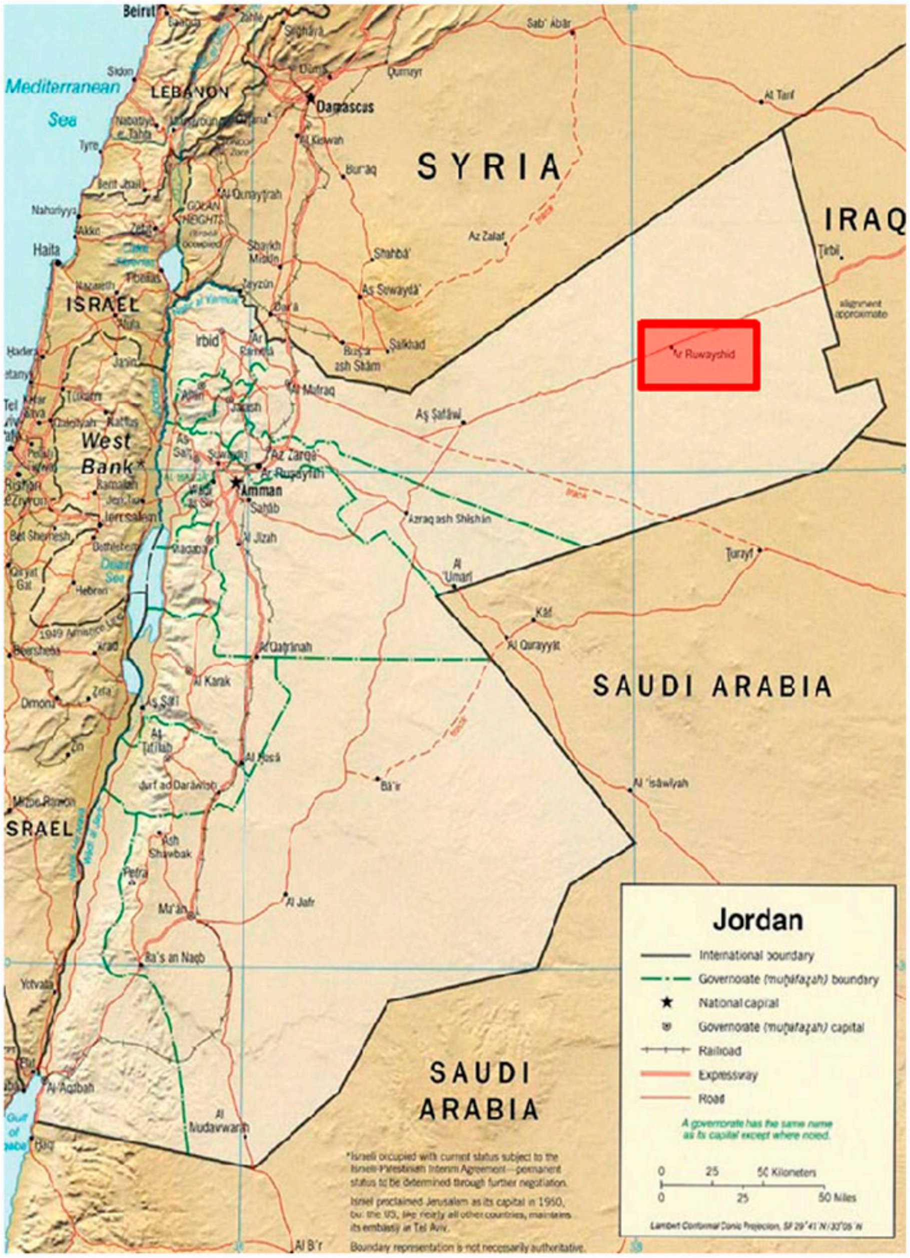

Fig. 8. Location of the innovative energy autonomous system in Jordan.

Table 5
Results of the analysis of the brackish water under study

	Date	pH unit	EC uS/cm	TDS mg/L	Hard mg/L		Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO_4^{2-} mg/L	CO_3^{2-} mg/L	HCO_3^- mg/L	NO_3^- mg/L	Turb NTU	SiO_2 mg/L	NH_4^+ mg/L	PO_4^{3-} mg/L	Mo mg/L	Sb mg/L
Sample 1	18/12/2010	7.23	2,730	1,775	882		162	108.42	229.8	11.8	300	459.4	0	392	0.6	41.5	19.04	2.6	0.15	<0.01	
Sample 2	18/12/2010																				
Sample 1	19/12/2010	7.23	2,720	1,768	907		182	109.51	208.4	10.9	295	457.9	0	384	<0.20	45.7		2.5		<0.01	
Sample 2	19/12/2010																				
Sample 1	20/12/2010	7.21	2,710	1,762	972		198	115.68	223.8	12.7	300	477.1	0	383	0.47	44.6		1.9		<0.01	
Sample 2	20/12/2010																				
Source	Date	Fe mg/L	Mn mg/L	Cu mg/L	Pb mg/L	Cr mg/L	Cd mg/L	Zn mg/L	Ni mg/L	S mg/L	F mg/L	Odor TON	ABS mg/L	Ag mg/L	Al mg/L	Se mg/L	As mg/L	CN mg/L	Ba mg/L	Total Coli MPN/ 100 mL	Fecal Coli MPN/ 100 mL
Sample 1	18/12/2010	1.15	0.05	<0.01	<0.01	<0.01	<0.003	<0.06	<0.01	16.4	<0.20		<0.02	<0.01	<0.01	0.006	<0.005	<0.05	0.08	<1.8	
Sample 2	18/12/2010																			<1.8	
Sample 1	19/12/2010	1.1	0.05	<0.01	<0.01	<0.01	<0.003	<0.06	<0.01	15.8	<0.20		<0.02		<0.01	0.007	<0.005			<1.8	
Sample 2	19/12/2010																			<1.8	
Sample 1	20/12/2010	2.96	0.06	<0.01	<0.01	<0.01	<0.003	<0.06	<0.01		<0.20		<0.02							<1.8	
Sample 2	20/12/2010																			<1.8	

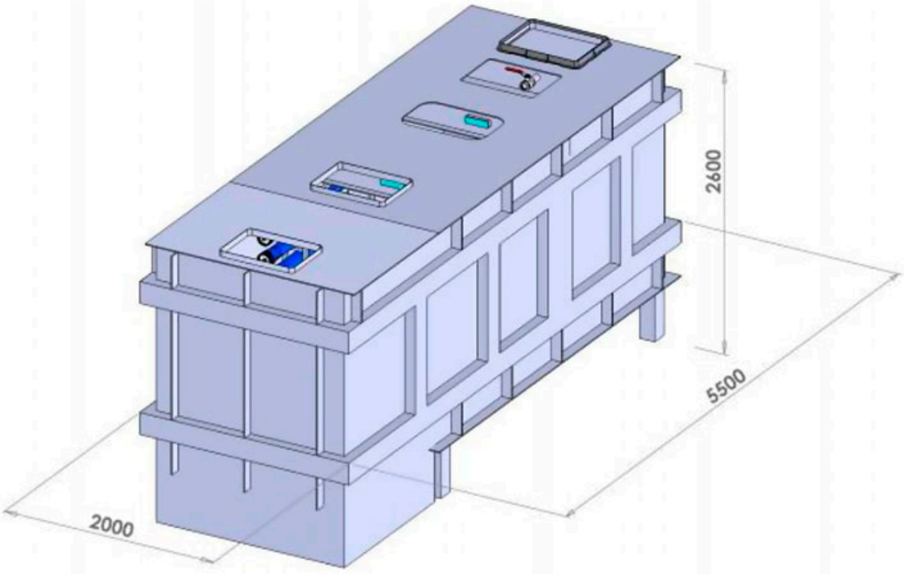

Fig. 9. Dimensions of the support base.

The fresh water production system and the water output taps are shown in Fig. 7. The citizens have access to water that fully complies with the standards of the World Health Organization (WHO).

3. Installation of the innovative system

After being operated and tested in Greece, the developed energy autonomous system for the production of drinking water from brackish water was transferred and installed in the Salhiyyat Al-Naeem Village of the Rwaished Municipality, in the eastern Jordan (distance from Rwaihsed to Salhiyyat Al-Naeem: ~35 km), as shown in the map of Jordan below (Fig. 8). Table 5 presents the results of the analysis of the brackish water of the Salhiyyat Al Naeem Village [21]. It is clearly shown that the conductivity is high and cannot be used as drinking water. The system was used to treat this particular type of water using RO with energy produced within the system. To achieve this, the appropriate installation took place.

A support base contains all control and functioning equipment. The dimensions of the support base are summarized in Fig. 9.

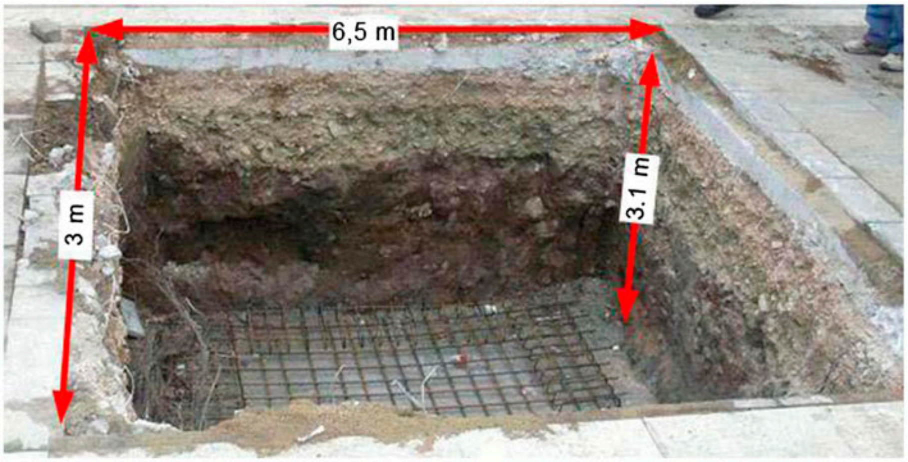

Fig. 10. Placement of the concrete base slab and wire mesh.

This support base was installed underground, as shown in Fig. 10. In order to ensure the safe installation and then the safe and proper operation of the whole system, the electrical cables, the telephone cables and any type of piping or sewer network were checked before the excavation so that it was confirmed that the suitable conditions were met. The rest of the system was installed above the underground metal base.

Indicative photos from the installation phase (October 2012) are provided below (Fig. 11).

The integrated installed system is shown in the following photos (Fig. 12).

The operation results show that the conductivity of the produced water was less than 400 μS/cm ensuring drinkable water specifications. Regarding the quality of the produced water, it should be noted that the control of the operating parameters of the system ensures the production of 40 m^3 of high quality drinking water in the outlet on a daily basis and TDS, Cl, SO_4^{2-}, Ca^{2+}, Mg^{2+}, F^-, NO_3^-, Cu^{2+}, Fe^{3+}, pH are well within standards of the WHO standards.

Fig. 11. Indicative photos taken during the installation phase in Jordan.

Fig. 12. Views of the full installed innovative system for the conversion of brackish water to drinking water (April 2013).

This decentralized innovative autonomous unit for drinking water provision has many advantages. The ease of installation, operation and maintenance of the unit makes it an ideal solution for remote arid areas. This source of drinking water will have positive impact on socio-economic growth of the area. The system provides a solution in areas when water transportation is difficult or extremely costly. Furthermore, lower losses of water transmission are achieved.

4. Conclusion

The developed innovative energy autonomous system provides a solution for drinking water in isolated small communities, using brackish water as feedstock. The composition of the produced water is well within the specifications of the WHO. The fact that the system is decentralized and there is no need for water transportation and consumption of electrical energy increases the value of the system and the reproduction potential in specific areas of Africa, Middle East, etc. with severe lack of water resources and low infrastructure with the electricity mainly produced by fossil fuels and/or lack of electricity grid connection.

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References

[1] United Nations, We Can End Poverty, Millennium Development Goals and beyond 2015, Factsheet, October 14, 2013. Available from: www.un.org/millenniumgoals/pdf/Goal_7_fs.pdf.

[2] R. Abedel Kahleq, Water Demand Management in Jordan. Ministry of Water and Irrigation (MWI), Amman, 2008.

[3] Ministry of Water and Irrigation, National Water Master Plan, Amman, 2004.

[4] H.A. Abu-Qdais, F. Batayneh, The role of desalination in bridging the water gap in Jordan, Desalination 150 (2002) 99–106.

[5] N. Hadadin, M. Qaqish, E. Akawwi, A. Bdour, Water shortage in Jordan—Sustainable solutions, Desalination 250 (2010) 197–202.

[6] B. Stanley, Growing Better Cities, Urban Agriculture for Sustainable Development, Dealing with the Water Deficit in Jordan, International Development Research Centre (IDRC), Ottawa, 2006.

[7] J.O. Jaber, M.S. Mohsen, Evaluation of non-conventional water resources supply in Jordan, Desalination 136 (2001) 83–92.

[8] M.J. Mohammad Rusan, S. Hinnawi, L. Rousan, Long term effect of wastewater irrigation on soil and crop quality parameters, Desalination 215 (2007) 143–152.

[9] B.M. Al-Qaisi, Geo-hydrological Study of Groundwater Artificial Recharge in Madoneh Area, MSc thesis not published, Mutah University, Mutah, 2008.

[10] Ministry of Water and Irrigation, Jordan's Water Strategy 2008–2022, Ministry of Water and Irrigation, Amman, 2009.

[11] M.S. Mohsen, Water strategies and potential of desalination in Jordan, Desalination 203 (2007) 27–46.

[12] M.S. Mohsen, J.O. Jaber, A photovoltaic-powered system for water desalination, Desalination 138 (2001) 129–136.

[13] IDA Worldwide Desalting Plants Inventory No. 17, Wangnick Consulting GMBH and IDA, 2002.

[14] Ministry of Water and Irrigation, Evaluation Study of the Brackish Water in Jordan, Ministry of Water and Irrigation, Amman, 2008.

[15] W. Meindertsma, W.G.J.H.M. van Sark, C. Lipchin, Renewable energy fueled desalination in Israel, Desalin. Water Treat. 13 January (1–3) (2010) 450–463.

[16] E. Tzen, M. Papapetrou, Promotion of renewable energy sources for water production through desalination, Desalin. Water Treat. 39 (2012) 302–307.

[17] M. Papapetrou, C. Epp, ProDes methodology for supporting the use of renewable energy systems in desalination applications, Desalin. Water Treat. 3 (2009) 204–209.

[18] H. Mohameed Qiblawey, M. Papapetrou, F. Banat, A strategy for the introduction of desalination powered by renewable energy in Jordan, Desalin. Water Treat. 3 (2009) 252–260.

[19] T.M. Missimer, Y.-D. Kim, R. Rachman, K. Choon Ng, Sustainable renewable energy seawater desalination using combined-cycle solar and geothermal heat sources, Desalin. Water Treat. 51 (2013) 1161–1170.

[20] L.G. Palacin, F. Tadeo, C. de Prada, J. Salazar, Operation of desalination plants using renewable energies and hybrid control, Desalin. Water Treat. 25 (2011) 119–126.

[21] APHA, AWWA, WEF, Standard methods for the examination of water and wastewater, 20th ed., American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC, 1998.