ECO-FRIENDLY DESIGN OF A SMALL SCALE PRESSURE RETARDED OSMOSIS POWER PLANT CLOSE TO THE SIMETO RIVER MOUTH

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Abstract – The osmotic pressure, obtained from the difference of salinity between fresh water of rivers and salt water from the sea, is one of the most promising technologies in the context of marine renewable energy.

The present work investigates a small-scale Pressure Retarded Osmosis (PRO) plant to be located along the eastern coast of Sicily (Italy), near the mouth of the Simeto River. After estimating PRO plant potential power production, in terms both of the availability of water resources and of local salinity gradients, in order to guarantee a low environmental impact and according to the principles of the "Green Economy", we paid attention to the materials adopted for the structure components and, looking at the educational function of the plant, we ideated the building interior design.

Concerning possible environmental impacts, the discharge dynamics in the nearshore region is investigated by means of hydrodynamic modelling, taking into account wave and current interactions close to the river mouth.

Riassunto – *Una delle tecnologie più promettenti nell'ambito delle fonti di energia rinnovabile è quella che utilizza la pressione osmotica, ottenuta dalla differenza di salinità tra l'acqua dolce di fiume e acqua salata di mare.*

Il presente lavoro analizza la fattibilità di un impianto Pressure Retarded Osmosis *(PRO) di piccola scala collocato lungo la costa della Sicilia orientale (Italia), vicino la foce del fiume Simeto. La stima del potenziale di produzione di energia dell'impianto PRO è stata fatta valutando sia la disponibilità di risorse idriche che il gradiente di salinità locale. Sono stati poi scelti i materiali adottati per la struttura, al fine di garantire un basso impatto ambientale e tenendo in considerazione i principi della "Green Economy", e progettati gli spazi interni, pensando alla funzione educativa che l'impianto potrebbe assumere.*

La dinamica della propagazione dei deflussi in uscita dall'impianto nella regione nearshore è stata studiata attraverso la modellazione numerica, tenendo conto della interazione tra onde e correnti osservata in prossimità della foce del fiume.

Introduction

Sustainable energy development has been subject to increasing attention during the past decade as a response to global energy challenges and socio-economic and political changes [14]. In order to give people a comfortable standard of living, many scholars are employed to fine new renewable resources that emitting fewer noxious chemicals.

The renewable energy on which is focused the society attention are solar, wind, biofuel, geothermal and hydro-power, but since 1954 Osmotic power, introduced by Pattle, is an attractive option. In fact the osmotic energy released from the mixing of fresh with salt water is a significant amount and osmotic power or salinity gradient energy as a renewable source of energy has attracted a lot of attention recently [1].

The global energy production potential of PRO (pressure-retarded osmosis) could reach up to 2 000 TW h per year against 10 000 TW h per years that are the estimated global energy production from all renewable source [2]. According to Altaee et al. (2014), osmotic energy is a promising renewable energy source.

Pressure Retarded Osmosis is a technique which enables the generation of electricity from the difference of molar free energy. The idea behind PRO is based on the fact that the water flows naturally from a low salinity solution (feed water) across a semi-permeable membrane to a more concentrated pressurized draw solution, driven by the osmotic pressure difference across the membrane. In fact, putting two solutions, with different salinity, in a compartment separated by a suitable membrane an osmotic flow can be observed. In this way, a pressurization of the volume in the concentrated salt solution compartment causes an increased hydraulic pressure difference over the membrane. By discharging the brackish effluent through hydro-turbine electricity power can be generated.

Figure 1 shows a schematically system operation.

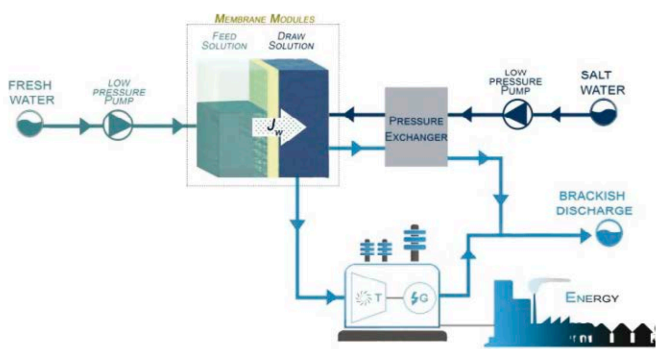

Figure 1 – Sketch of PRO.

The water flux across the membrane in PRO process is usually described by the following equation:

$$J_w = A(\Delta\pi_{osm} - \Delta P) \tag{1}$$

where *Jw* is the water flux per unit of membrane area in $m^3s^{-1}m^{-2}$, *A* is the water permeability coefficient of the membrane in $m^3s^{-1}kPa^{-1}m^{-2}$, $\Delta\pi_{osm}$ and ΔP are the theoretical osmotic pressure differential and the hydraulic pressure applied, both measured in *kPa*. The pressure difference ($\Delta\pi_{osm}$ - ΔP) represents the effective pressure difference at the membrane of the PRO system.

The power density W, in W=m^2, which can be generated per unit membrane area, is the product of the water flux J_w and of the hydraulic pressure differential across the membrane ΔP in kPa:

$$W = J_W \Delta P = A(\Delta\pi_{osm} - \Delta P)\Delta P \quad (2)$$

Moreover in PRO processes, since $\Delta P < \Delta\pi_{osm}$, it was demonstrated that the maximum power density is obtained when $\Delta P = \Delta\pi_{osm}$=2 [8][10][20]. This equation gives the theoretical specific power density of a PRO system. However, membranes are susceptible to phenomena which reduce the effective osmotic pressure difference. For a detailed analysis see [13][3][20].

Besides the osmotic flux related to the characteristics of the semipermeable membrane, the evaluation of the performance of the whole system must take into account the efficiency of the hydraulic and the used electric machines. The gross power W_{gross} generated by the PRO plant is defined as [12]:

$$W_{gross} = \Delta P_{eff} Q_{permeate} \eta_{turbine} \eta_{generator} \quad (3)$$

where ΔP_{eff} is the effective osmotic difference at the end of the process, $Q_{permeate}$ is the permeate discharge flowing through the membrane, $\eta_{turbine}$ and $\eta_{generator}$ are respectively the turbine and the generator efficiencies.

Finally, other important design parameters are the ratio between fresh water and salt water discharge, which should be Q_d=Q_f= 2 [15][18] and between permeate and fresh water discharge Q_p=Q_f= 0,8 [18].

The aim of this study is to design a PRO plant and the building that will host it, according to the principles of the "Green Economy". Two aspects of the project are discussed: the PRO plant energy production and the environmental impact of the structure.

From the power production viewpoint, PRO design method is applied in order to estimate potential power production in terms both of the availability of water resources and of local salinity gradients. Moreover, the discharge dynamics in the nearshore region is investigated by means of hydrodynamic modelling, taking into account wave and current interactions close to the river mouth. The results of numerical simulations have been analysed in order to determine the influence area of the brackish discharge of the plant, to quantify the effect of deviating fresh and salt water from river and offshore regions and the effect of discharging the resulting brackish water near the river mouth. Indeed as a consequence of a different salinity distribution in the nearshore zone, potential ecological impact may arise.

Regarding the plant structural design, in order to guarantee a low environmental impact we paid attention to the choice of the materials adopted for the structure and to the building design, ideated also considering the educational function of the plant (i.e. educational laboratories and exposition area). The study should demonstrate that, despite the specific location close to Simeto mouth, the eco-friendly realization of a PRO plant is feasible.

Site study

The majority of PRO researches are focused on mixing of seawater and river water [19]. The most relevant basin of Sicily is the Simeto's basin, with its 4200 km^2 catchment area.

In the 1984 the Simeto mouth area, with an extension of 2 000 ha, was established as natural reserve.

To determine the suitable site to build the PRO plant different types of analysis have been carried out:

- Hydraulic and hydrologic analysis, to evaluate the expected persistence of the river water discharge during an average year (Figure 2);
- Salinity concentration analysis along the river, to determine an optimal location for the river water intake;
- Road traffic and power lines system analysis, to secure a strategic position for use of energy (Figure 3);
- Environmental protection system analysis, to prevent damaging and not to alter the ecosystem of the Simeto Oasis protected area (Figure 4);
- Hydraulic risks analysis, to consider the delimitation of flood areas (Figure 5).

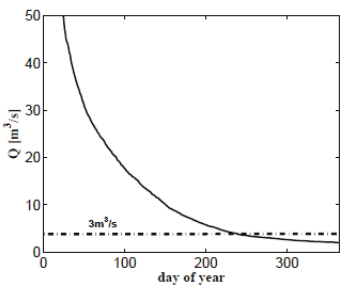

Figure 2 – Water discharge available at the Giarretta Station over an avenge years, determined through a statistical analysis of a data-set which covers more than 36 years (from 1931 to 1967).

Figure 3 – Road traffic and power lines system analysis.

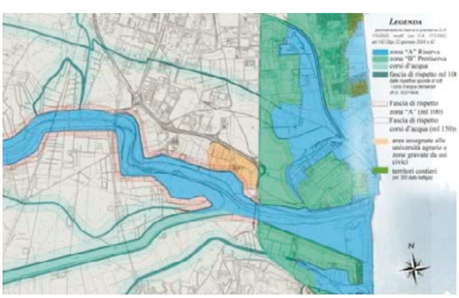

Figure 4 – Environmental protection system analysis.

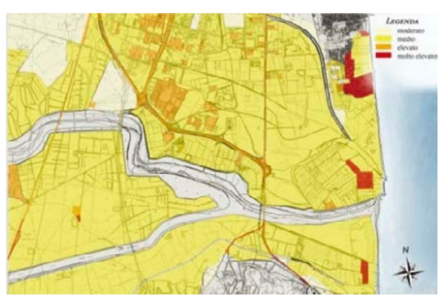

Figure 5 – Hydraulic risks analysis.

Thanks to the first analysis, by using data coming Giarretta hydrometric station, it turns out that the water discharge available for more than 240 days per year is about 3 m^3s^{-1}.

Thanks to all these analyses, the position chosen for the PRO plant is 6.5 km upstream of the estuary, nearby a node of the electric network and the extended industrial area of Catania and in such a way as to ensure a gravity driven river water supply to the plant. Indeed the elevation difference between the fresh water intake and the plant is about 5 m, which allow overcoming all possible energy losses. The salt water intake is located at an offshore area close to the river mouth, at a water depth of about 5 m, so the draw solution supply must be provided. The plant is located at 10 m above sea level. The suitable location for the plant installation is shown in Figure 6.

Concerning the wave forcing along the coast, data about the yearly average wave climate are considered, to characterize the investigated area. The analysis reveals that the wave climate is mainly characterized by waves coming from the East (40°, 90° and 135°), in terms of frequency and significant wave height, with the most frequent wave heights in the range 0.5 ÷ 3 m.

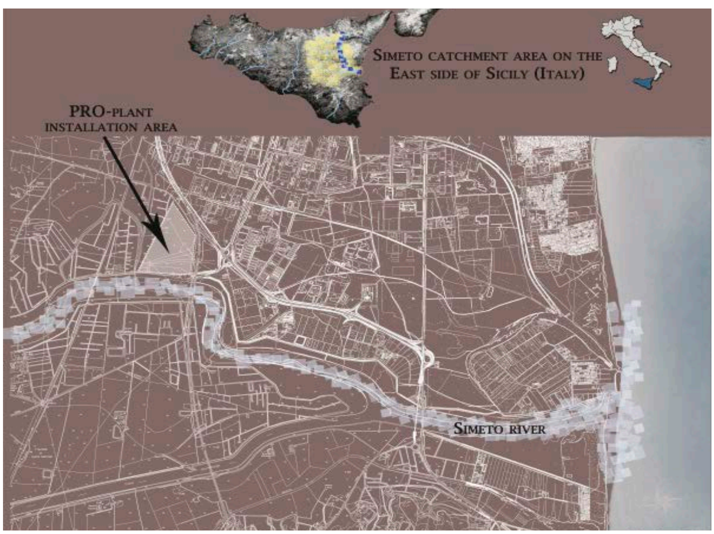

Figure 6 – Simeto catchment area and location of PRO plant installation area.

PRO plant design

The design of PRO plant depends on three parameters: osmotic pressure difference, fresh water intake availability and characteristics of the PRO plant membrane.

The first two parameters are related to the choice of the plant installation area.

In the case being, the osmotic pressure difference is calculated using eq. 1, which gives $\Delta\pi_{osm}$= 2900 kPa, considering that the salinity concentration of fresh water (Simeto River) is about 0.1 g l^{-1}, while the salinity concentration of salt water (Ionian Sea) is about 35 g l^{-1}.

The maximum power density W is obtained when the hydraulic pressure ΔP is equal to half of the osmotic pressure $\Delta\pi_{osm}$ [8], but a significant deviation may occur when the osmotic pressure increases and the ratio of the feed and draw flow varies [5]. To extract the maximum power density condition a volumetric ratio 0.5 for the feed and draw solution has been selected [7]. Considering that the Simeto River guarantee a water discharge of 3 m^2/s, a sea water intake of 6 m^3s^{-1} is required.

The weak point of PRO technology is the efficiency of the membranes. Indeed, no hollow fiber semi-permeable membranes have yet been developed and optimized to meet the requirement of PRO applications and we can say that they are still in their “infancy”. To choose the suitable membrane, the performances of a flat sheet cellulose triacetate (CTA) Forward Osmosis (FO) membrane and hollow fibre (HF) spiral wound membrane have been compared. The processes, which reduce the effective osmotic pressure difference across the membrane, are salt reverse diffusion and even more severe phenomena such as the concentration polarization (accounting both for external and internal polarization). The effects of the above process can be evaluated if the membrane coefficients, i.e. the water permeability coefficient A, the salt permeability coefficient B, the external concentration polarization mass transfer coefficient k, and the internal concentration polarization mass transfer coefficient K, are known. The values of such parameters are based on the work of Achilli et al. (2009), in the case of flat sheet cellulose triacetate FO membrane, and on the work of Han et al. (2014) in the case of spiral wound membranes. For each membrane type, the value of power density obtained both in the ideal case, in which salt reverse diffusion and concentration polarization are not taken into account, and in the complete case, in which the effects of such processes are considered, are reported. As expected, a much higher maximum power density (8.5 W m^{-2}) is obtained in the case of the hollow fiber spiral wound membrane with respect to flat sheet cellulose triacetate membrane (3.5 W m^{-2}). Considering the complete case, the effective osmotic difference at the membrane $\Delta\pi_{osmeff}$, and consequently the hydraulic pressure difference ΔP applied at the draw solution, is slightly higher for CTA membrane ($\Delta\pi_{osmeff}$ =2690 kPa and ΔP_{eff}=1350 kPa/m^3) when compared with the HF membrane ($\Delta\pi_{osmeff}$=2680 kPa and ΔP_{eff}=1340 kPa/m^3).

If the turbine and generator efficiencies are to be taken equal to 0.85 (η_t e η_g) and the permeate discharge is to be taken equal to 2.4 m^3s^{-1} (Q_p), the power plant capacity is estimated about 2.7 MW for both of the selected membrane, but the areas of membrane needed are different. Indeed, for the HF membrane is required an area of about 380 000 m^2, while for the CTA membrane is about 915 000 m^2. Considering a membrane packing density of 775 m^2m^{-3}, with stack height equal to 3 m and stack length of 10 m, 12 membrane stacks are needed for the HF plant while 30 membrane stacks are needed for CTA plant.

In order to optimize the provided power density, energy losses due to the spatial variations along the membrane have to be taken into account [7]. Such energy losses throughout the system represent loads that must be provided by the pump. Considering the gross power and the losses due to the pumps, the determination of the net power of the plant is important [12]. In this case a pumping system is required only for the draw solution from the sea. The pumping system has been designed considering a pipe diameter of 2 m and an efficiency of 0.75. The power required is equal to about 1.6 MW. Therefore, net power of the considered PRO plant would be about 1.1 MW. It follows that power reduction of the 40 % of the gross power capacity P_{gross} is due to the energy required by the pumping system.

Building design and its environmental impact

The building hosting the PRO plant is designed, according to the principles of the "Green Economy" and in a way to guarantee a low environmental impacts.

The building shape is ideated, proposing a low visual environmental impact configuration. In particular a "dug and built structure" presenting a green roof architecture and a wooden construction is designed. Figure 7 shows two different views of the 3D model of the PRO plant building.

The "dug and built structure" presents an extension of 2 meters in the underground direction and an extension of 4 meters above the terrain level. The dimension of the underground structure allows the installation of ribbon windows, ensuring a good window-to-floor area ratio.

The interior design of the structure is divided in two floors, which are ideated in order to contain not only the technical plant components (located in the lower level) but also to allow educational activities. Therefore the structure contains also: visitor center with an exposition area, pedestrian visitor paths and experimental laboratory. The visitor entrance is located on the upper floor, directly from the sloping roof. A walking way along the perimeter of the building is designed, working as terraces from which it is possible to see the different components of the plant. The walking way is designed aiming at educational goals. Visitors are allowed to go downstairs, in a underground room, where an expositive area is organized and where eventually multimedia exposition about the PRO plant functioning could be realized.

Figure 7 – View of the building 3D.

Regarding the green roof, it offers the opportunity to enjoy a nice panoramic view seeing: the Etna volcano on the north direction, the Simeto river on the south direction and the Ionian sea on the east direction. The roof of the structure is a sloping plan, with a gradient of 6 % - 8 %, which provides a natural habitat. It is a widely accepted form of green infrastructure deployed around the world to contribute to building efficiency and climatechange mitigation and adaptation through improved thermoregulation and water capture [11]. Indeed, the green roof substrates provide insulation and the vegetation contributes to cooling via shading, reflection of solar radiation and evapotranspiration of water. These cooling effects improve building energy balance and the resulting artificial warming of surrounding air temperature. The application of green roofs is widespread and significant benefits to building owners and users by improving thermal efficiency, energy savings and mitigation of the urban heat island. Moreover, this kind of covering mitigates the effects of pollution acting as a filter, improves the building insulation (heating - cooling) increasing the building energy efficiency, reduces noises resulting in a more comfortable environment.

The main material used for the building design is cross-laminated (X-lam). The X-Lam system is based on the use of panels made of layers of timber boards with the adjacent layers glued under pressure at a right angle [17]. The main advantage of the system is the speed of construction since all the panels are prefabricated off-site, cut to size, delivered to the building site and then easily connected using metal connectors. Moreover, they are large structural elements, ranging usually between 2.40 and 2.95 m wide and up to 16.50 m long [6], able to cover large span.

From the architectural point of view the use of X-lam material means to design adopting a sustainable building material, with energy saving properties that will represent an active contribution to climate protection. X-LAM construction meets the requirements of environmental and passive energy standards, thanks to its high energy efficiency, low greenhouse emissions and small environmental impact. Moreover, a reduced wall construction thickness enables more space within the structure and it easily integrates with other materials. The panels can be visible directely from the interior, providing a natural finishing or clad with other materials and they require little or no maintenance.

Regarding the structural benefits, X-lam has a high axial load capacity and high shear strength from horizontal loading. Moreover, it offers significant advantages to fire protection, improves air tightness and provides excellent acoustic performance.

Environmental impact of discharge dynamics

The dynamics of the brackish discharge has been numerically investigated based both on the plant effluent characteristics and on the river discharge and wave climate.

The hydrodynamic model used are CMS-Wave and CMS-flow, designed for simulating currents, waves, sediment transport and morphology change in coastal areas. The CMS-Wave model was used in order to simulate the wave propagation from offshore to the nearshore zone, by including wave shoaling, refraction-diffraction and breaking processes. The output of the wave model (i.e. wave heights, peak wave periods, wave direction, etc.) is used as the input of the CMS-flow simulation of the nearshore hydrodynamics. The results of hydrodynamic model provide information about the dynamics of the PRO plant brackish effluent in terms of plume extension, current velocity and direction as a function of the specific wave climate conditions.

By taking into account different simulated scenarios, it appears that the difference in terms of salinity caused by effluent discharge is low if compared to the seasonal salinity variability of the selected site. Indeed, the maximum estimated fluctuation determined by the presence of the plant effluent discharge in terms of dilution is 40 % of the average annual ambient seawater salinity concentration, while the seasonal variability in the same coastal area is about 100 %.

Moreover, the results demonstrate that the plume extension in the offshore direction is of the order of about 300 m and it is relevant for the optimal position of draw solution intake, in order to avoid problems of salinity recirculation. Thus, the sea intake should be suitably located outside of the surf zone, more or less 150-200 m far from the shoreline.

Conclusions

The feasibility of a small-scale PRO plant located close to a river mouth along the coast has been evaluated in terms of possible energy production and environmental impact, from the building design and the hydrodynamics of effluent discharge point of view.

Considering a fresh water intake of 3 m^3s^{-1} coming from the Simeto River, which is guaranteed at least 230 days per year, and a salt water intake coming from the Ionian Sea, the results on the analyzed case highlight the potential of the PRO technology. In particular, the power plant is estimated about 2.7 MW. Taking in account the required power for pumping system, the net power is about 1.1 MW. After the analysis of the river mouth area, the location of the optimal position of the plant is determined.

The building plant was designed according to the Green Economy and in order to guarantee a low environmental impact. The main structure material is X-LAM, which meets the requirements of environmental and passive energy standards. Moreover, to mitigate the visual impact, the construction is a “dug and built structure” with a sloping vegetated roof. The building is designed also for hosting educational activities.

Concerning the impact of the discharge, thanks to the hydrodynamic analysis it is possible to demonstrate that the small discharge of the brackish effluent is not capable of dramatically changing the salinity distribution along the coast, which is primarily dominated by the presence of the Simeto River. Indeed, the seasonal variability of the salinity concentration in the same coastal area is about 100 % of the offshore seawater salt concentration, while the maximum fluctuation of dilution of salinity concentration due to the PRO plant effluent is about 40 %. Since the salinity dilution due to the PRO plant presence is lower than that due to the Simeto seasonal variability, it is reasonable to assume that many marine organism should be naturally adapted to such changes.

In conclusion, the net power achievable by the present plant is comparable with all other source of renewable energy. The advantages of the PRO plant technology are related to the continuity in time of the plant operation and also to the production of energy in coastal areas, where the energy demand is higher.

References

[1] Abbasi-Garravand, E., Mulligan, C. N., Laflamme, C. B., & Clairet, G. (2016). *Role of two different pretreatment methods in osmotic power (salinity gradient energy) generation*. Renewable Energy, 96, 98-119. doi:10.1016/j.renene.2016.04.031

[2] Achilli, A., Cath, T.Y., Childress, A.E., (2009). *Power generation with pressure retarded osmosis: An experimental and theoretical investigation*, Journal of Membrane Science, 343 (2009), 42-52.doi:10.1016/j.memsci.2009.07.006

[3] Achilli, A., Childress, A.E. (2010). *Pressure retarded osmosis: From the vision of Sidney Loeb to the first prototype installation - Review*, Desalination, 261 (2010), 205-211.

[4] Altaee, A., Zaragoza, G., Sharif, A. (2014). *Pressure retarded osmosis for power generation and seawater desalination: Performance analysis*, Desali nation, 344 (2014), 108115.

[5] Banchik, L.D., Sharqawy, M.H., Lienhard V, J.H. (2014). *Limits of power production due to finite membrane area in pressure retarded osmosis*, Journal of Membrane Science, 468 (2014), pp. 81-89

[6] Jorge, L., Dias, A., & Costa, R. (2015). *Performance of X-lam panels in a sports center with an indoor swimming-pool.* Journal of Civil Structural Health Monitoring, *5*(2), 129-139. doi:10.1007/s13349-014-0090-7

[7] He, W., Wang, Y., Shaheed, M. H., (2014). En*ergy and thermodynamic analysis of power generation using a natural salinity gradient based pressure retarded osmosis process*, Desalination, 350 (2014) 86-94.

[8] Lee, K., Baker, R., Lonsdale, H., (1981). *Membranes for power generation by pressure retarded osmosis*, Journal of Membrane Science, 8 (1981) 141171.

[9] Loeb, S., (1975). *Osmotic power plants*, Science, 189 (1975) 654-655.

[10] Lin, S., Straub, A.P., Elimelech, M., (2014). *Thermodynamic limits of extractable energy by pressure retarded osmosis,* Energy Environmental Science, 2014, 7, 2706-2714. DOI:10.1039/c4ee01020e

[11] MacIvor, J. S., Margolis, L., Perotto, M., & Drake, J. A. P. (2016). *Air temperature cooling by extensive green roofs in Toronto Canada.* Ecological Engineering*, 95*, 36-42. doi:10.1016/j.ecoleng.2016.06.050

[12] Maisonneuve, J., Pillay, P., Laflamme, C.B. (2015). *Pressure retarded osmotic power system model considering non ideal effects,* Renewable Energy, 75 (2015) 416-424.

[13] McCutcheon, J.R., and Elimelech, M., (2006). *Influence of concentrative and dilutive internal concentration polarization on flux behavior in forward osmosis*, Journal of membrane science, 284 (1-2) (2006), 237-247.

[14] Mosannenzadeh, F., Bisello, A., Diamantini, C., Stellin, G., & Vettorato, D. (2017). *A case-based learning methodology to predict barriers to implementation of smart and sustainable urban energy projects*. Cities, 60, 28-36. doi:10.1016/j.cities.2016.07.007

[15] Naghiloo, A., Abbaspour, M., Ivatloo, B.M., Bakhtari, K., (2015). *Modeling and design of a 25 MW osmotic power plant (PRO) on Bahmanshir River of Iran*, Renewable Energy, 78 (2015), 51-59

[16] Pattle, R.E. (1954). *Production of electric power by mixing fresh and salt water in the hydroelectric pile,* Nature, 174 (1954), 660.

[17] Rinaldin, G., & Fragiacomo, M. (2016). *Non-linear simulation of shaking-table tests on 3- and 7-storey X-lam timber buildings*. Engineering Structures, *113*, 133-148. doi:10.1016/j.engstruct.2016.01.055
[18] Thorsen, T., Holt, T., (2009). *The potential for power production from salinity gradients by pressure retarded osmosis*, Journal of Mem brane Science, Vol. 335, Issues 12, pp 103-110, ISSN 0376-7388, http://dx.doi.org/10.1016/j.memsci.2009.03.003.
[19] Wan, C. F., & Chung, T. (2015). *Osmotic power generation by pressure retarded osmosis using seawater brine as the draw solution and wastewater retentate as the feed.* Journal of Membrane Science, *479*, 148-158. doi:10.1016/j.memsci.2014.12.036
[20] Yip, N.Y., Tiraferri, A., Phillip, W.A., Schiffman, J.D., Hoover, L.A., Kim, Y.C., Elimelech, M., (2011). *Thin-Film Composite Pressure Retarded Osmosis Membranes for Sustainable Power Generation from Salinity Gradients*, Environ. Sci. Technol., 45 (10), 43604369.