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THINK

POLICY BRIEF

# A COST-EFFECTIVE LOW-CARBON FRAMEWORK TO MANAGE EMISSIONS FROM WATER DESALINATION

Task Force 2
**CLIMATE CHANGE AND ENVIRONMENT**

Authors
**MALAK AL-NORY, MOHAMMED ANTAR, ALEXANDER BRODSKY, STEPHEN GRAVES, HUSSAMELDIN KHONKAR, JOHN LIENHARD, KHULOOD RAMBO, SA'D SHANNAK**

موجز السياسة

# إدارة الانبعاثات من تحلية المياه باستخدام إطار عمل فعّال من حيث التكلفة ومنخفض نسبة الكربون

فريق العمل الثاني

**تغير المناخ والبيئة**

المؤلفون

**ملك النوري، محمد عنتر، ألكسندر برودسكي، ستيفن جريفز، حسام الدين خونكار، جون لينهارد، خلود رامبو، سعد شنك**

# ABSTRACT

The commitment undertaken by G20 countries to lower their carbon emissions levels makes renewable energy-powered water desalination especially valuable, given that almost half the global water desalination capacity is installed in these countries. Recent installations have shown that Reverse Osmosis (RO) operated by Solar PV is extremely suitable for green desalination. G20 countries should adopt Photovoltaic Reverse Osmosis (PVRO) with water storage for cost-effective and low-carbon water desalination. They should include PVRO projects within the structured financing available for renewable energy projects. The G20 countries with the largest desalination and renewable energy capacities may sign a Cooperative Framework Agreement to establish a global cooperation platform.

نتيجـة التـزام دول مجموعـة العشـرين بتخفيـض مسـتويات انبعاثـات الكربـون لديهـا، أصبحـت تحليـة الميـاه باسـتخدام الطاقـة المتجـددة قيّمـة علـى نحـو خـاص، خصوصـا أن نصـف الطاقـة الاسـتيعابية تقريبًـا لتحليـة المياه علـى مسـتوى العالـم توجـد فـي دول مجموعـة العشـرين. وتُظهـر منشـآت حديثـة أن التناضـح العكسـي، الـذي يعمـل بالألـواح الضوئيـة الشمسـية؛ يُعـد طريقـة مناسـبة لتحليـة الميـاه بشـكل صديـق للبيئـة، وينبغـي لـدول مجموعـة العشـرين أن تتبنـى التناضـح العكسـي بالألـواح الشمسـية، مـع تخزيـن الميـاه مـن أجـل تحليـة الميـاه بطريقـةٍ فعَّالـة مـن حيـث التكلفـة ومنخفضـة الكربـون. كمـا ينبغـي لحكومـات مجموعـة العشـرين أن تُـدرج مشـروعات التناضـح العكسـي بالألـواح الشمسـية فـي التمويـل المنظّـم لمشـروعات الطاقـة المتجـددة. ومـن المرجـح أن توقـع دول مجموعـة العشـرين، التـي تمتلـك أكبـر طاقـة اسـتيعابية لتحليـة الميـاه والطاقـة المتجـددة، اتفاقيـة إطاريـة تعاونيـة مـن أجـل تدشـين منصـة تعـاون عالميـة.

# CHALLENGE

This policy brief promotes renewable energy-powered water desalination with PVRO technology as a mechanism for creating an integrated and sustainable solution for both clean water production and energy storage. It presents the key technology, implementation, and replication-related interventions required to enable a cost-effective low-carbon framework to manage emissions with water desalination. It aims to enable the G20 countries to realize higher levels of renewable energy integration in the energy mix and to realize major aspects of a circular economy.

G20 countries contribute to about 48% of the total water desalination capacity in the world with about 52,264.5 mm3/day. The minimum energy required to produce this amount of fresh water using best large-scale commercial technology available today is 209,057.9 MWh/day, which will result in about 93,030.8 tons/day of CO2 emissions. The G20 can reduce total emissions by 209,057 tons/day after committing to PVRO. This can lead to an emission reduction of 428,000 tons/day globally, if other countries also learn from the experience of the G20 countries. If the G20 countries switch to water storage in place of the currently expensive energy storage mechanism as per the proposed framework, it will result in huge cost reductions (approx. 722,817 mn$) in desalination projects (See Appendix [I] for analysis and assumptions).

Clean energy can power global recovery from COVID-19, especially because the pandemic hit the world's poorest regions and the elderly (with respiratory and cardiovascular diseases and diabetes, and in countries with high levels of pollution) the hardest, and also affected the most vulnerable and fragile communities by adding unprecedented health and economic burdens to the existing poverty and climate crises. Thus, a comprehensive and collaborative response is necessary. Clean energy lies at the root of such collaborations, as it can provide affordable solutions in line with climate targets and can help mitigate the effects of the pandemic on people's livelihoods and local economies (Alers 2020; Wooders and Gerasimchuk 2020).

Recent installations have confirmed that RO operated by PV power is highly suitable for green desalination. However, the costs of desalination projects have increased dramatically because of the additional components of PV and energy storage. The integration of renewable energy sources in the energy mix has increased the complexity of power grid management because of the variability and intermittent nature of these energy sources. Energy storage solutions such as batteries offer either short-term storage options that are insufficient or long-term ones that are significantly expensive, both economically and environmentally. The sustainability of driving RO desalination units with renewable energy sources faces technical challenges that can be resolved with collaboration among the G20 countries. These challenges include PV technology reliance on rare earth elements that are available only in a few countries, high capital cost of energy storage, membrane fouling issues, low efficiency of pretreatment processes, and the lack of policies for the efficient management and monitoring of the by-products of desalination (brine) (see Appendix [II] for a detailed discussion on technical challenges). The capital cost of traditional installations of PVRO constitutes the main challenge. This policy brief provides the G20 with an attractive solution to overcome these challenges so that renewable desalination can cost less and be made available widely, while also being environmentally benign.

# PROPOSAL

### Proposal 1

The G20 should include PVRO technology as an innovative solution to complement previous efforts on Grid Integration for Variable Renewables (GIVAR) implemented by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). This option can provide a broader range of countries with low-cost and eco-friendly solutions for the production of fresh water while simultaneously increasing the integration of renewable energy sources into the power grid. This controls the unfavorable variability of renewable energy sources, and achieves large reductions in cost and carbon emissions.

This proposal describes how renewable desalination with sufficient storage capacities ensures efficient generation, storage, and management of water desalination, and addresses multiple energy and climate change challenges. The technology uses photovoltaic solar panels as the renewable energy source to power RO desalination plants. Thus, the proposed technology is PVRO.

RO desalination plants with appropriate technologies can implement a two-way link in which the plant can import electricity only when necessary. It will export energy when there is excess. It will also act as a storage device and export electricity to the grid during a power shortage. Water distribution systems will have storage capacity for the same reasons. The operating storage is usually two hours of an average day flow that is, operating storage = (average day demand/24 hours) x 2 hours. Aquifer storage and recovery (ASR) systems located strategically near water facilities can house billions of cubic meters of desalinated water for strategic long-term storage (Missimer, Sinha, and Ghaffour 2012). With appropriate smart controls, the RO desalination plants in this framework can act as power generators from multiple sources (PV and power grid) based on the supply and demand scheduled for a period. These plants will also act as virtual batteries for the power grid and are capable of delivering the required power for a time period. Excess power from renewable sources can be directed to the power grid whenever power generation is expensive and can be switched back when the level of stored water needs to be addressed (Al-Nory and El-Beltagy 2014; Al-Nory and Brodsky 2014).

The RO plant is coupled with the grid and the PV sources are used as fuel substitutes in case of interruptions to grid supply (Tzen and Richard 2003). The PV source is also coupled with the grid to supply power directly when power demand is high. Electricity consumption levels for typical desalination operations using RO with energy recovery are 3–4 kWh/m3 for feed water salinity of 25,000ppm (Al-Nory and Graves 2003; Al-Nory and Graves 2013).

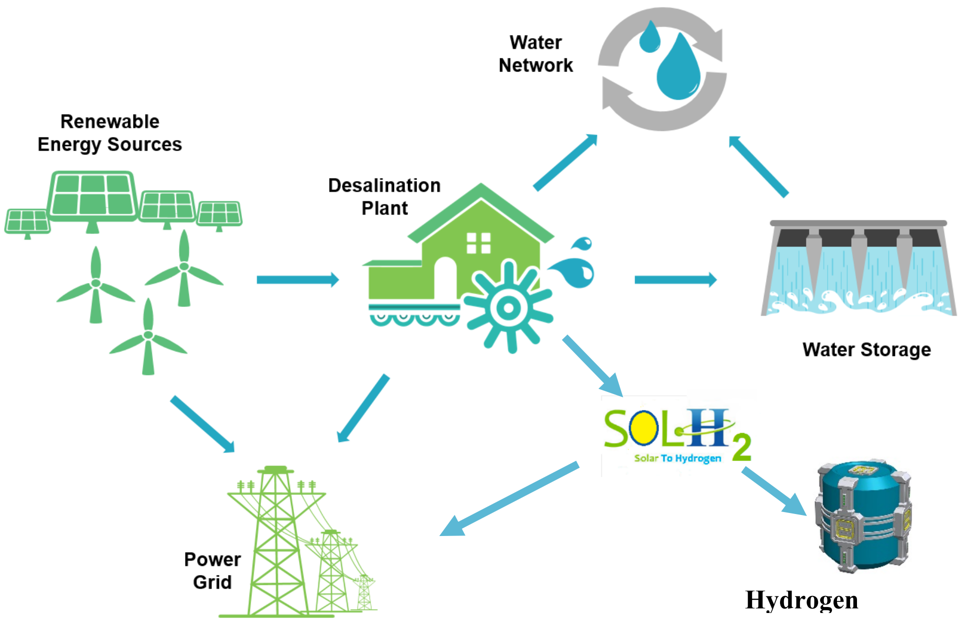


Figure 1: **Schematic View of the Framework**

The proposed framework can be extended to fulfill the goal of securing energy vectors from renewable energy sources by using solar power to produce hydrogen from water. It can contribute to the economic development of the country in question without causing additional environmental strains. An integrated hydrogen production system from water using PV solar connected to a board electrolyzer will maximize performance. The objective is to obtain at least 10% solar to hydrogen efficiency overall, in order to provide hydrogen from pure water to chemical and transport industries at the low competitive international price of $3/kg and No GHG emission (Jia et al. 2016; Esposito 2017; Kosturiak et al. 2019) (Figure 1).

The increased integration of renewable energy sources into the power grid can control unfavorable variability in renewable energy sources and reduce cost and emissions (Al-Nory and El-Beltagy 2014)—some of the many advantages that can be realized from implementing this framework.

### Proposal 2

The G20 should institutionalize and incentivize PVRO desalination plants under the G20 framework, as part of its collaborative efforts to support the implementation of the G20 Toolkit of Voluntary Options on Renewable Energy Deployment, and within the available resources including renewable energy technology cost analysis, renewable energy investment risk mitigation mechanisms and structured financing options, and the renewable energy map.

Among the G20 countries, at least eight have measurable water desalination capacities (see Appendix [I]). PVRO projects incur large capital and minimal operational costs because they include PV modules and RO desalination installations. The framework in proposal #1 achieves large cost and emission reductions (see Appendix [I] for a detailed financial analysis).

When renewable energy became available, governmental support was oriented toward investigating alternatives to fossil fuel power. The aim was to look at economically viable options based on whether renewable sources can produce electricity cheaper than fossil fuels. Other measures defining economic viability, such as environment and carbon emissions avoidance, were not heavily investigated at a site-level. Although some projects have looked at these measures (Trieb 2002; Kouta et al. 2016; Garmana and Mutasserb 2008; Ghorbani, Mehrpooya, and Ghasemzadeh 2018) using modeling tools and estimated data, none of them, to the best of the authors' knowledge, have looked at real projects and evaluated real data.

We can draw lessons from the Solar Seawater Reverse Osmosis Desalination project (Solar SWRO) located outside the urban boundary and close to Al Khafji with a capacity of 30,000 m3/day. The project meets the needs of 100,000 residents of Al Khafji in Saudi Arabia (see Figure 2 in Appendix [III]).

This project has been initiated by King Abdulaziz City for Science and Technology (KACST) and is the first large-scale plant in the world to be operated by solar energy. Solar SWRO was commissioned in April 2019 and has been operating since then. This plant is the only source of fresh water for inhabitants at the location. This project is located within a unique environment with complex factors, including high salinity, presence of oils and grease, sea shallowness, seasonal red tides, and jellyfish. A photovoltaic-powered seawater reverse osmosis desalination system is integrated into the current medium voltage bars of a common future 13.8kV /134kV power substation built by the Saudi Electricity Company (see Figure 3 in Appendix [III]).

This integration will result in a net-zero emission balance, meaning that the total energy produced by the project shall be equal to or higher than the energy requirements of the Khafji Solar SWRO plant in a 25-year period, which is estimated to be 86,000 MWh/year. This project is unique in the region as it applies advanced nanotechnologies in photovoltaic and RO membrane systems. This technology will limit the cost of energy production to 8.8 Saudi Halalas (0.025 $ per kilowatt-hour) and fully couple solar generation with the grid.

Drawing from the experience of the Khafji Solar SWRO project, we highlight a few key implications for policymakers to consider while establishing similar projects in order to achieve higher success in attracting investments for such projects:

- PVRO projects incur large capital costs and minimal operational costs because they include two installations, namely PV modules and an RO desalination unit (see Appendix [I] for a detailed financial analysis). Investors should use existing renewable energy investment risk mitigation mechanisms and structured financing options for renewable energy projects in the country, in order to finance PVRO projects. This will offer an incentive to invest in renewable desalination projects.

- Early projects should be established as Public-Private-Partnerships (PPP) and Power Purchase Agreements (PPAs) should be provided. This offers assurance to project investors to sell products through pre-established agreements.

- It is necessary to support private sector projects with fair energy exchange rates with a power grid either at the same consumption rate or at higher rates with a minimal ratio. This is needed to utilize the renewable energy capacity and to encourage higher capacity installation, which will, in turn, lead to meeting the national renewable energy targets.

- The incentives may include a reduced rate of energy consumption from the grid for desalination plants collaborating in this framework. Desalination plants may be motivated by the reduced rate of energy consumption or a more flexible pricing scheme that creates a market interface between power production and the desalination plant. In the interface, instead of a fixed power demand or commitment that the desalination plant has to provide, the amount can be variable.

**Proposal 3**

G20 governments should provide a platform for global cooperation with respect to renewable desalination replication models; these can be voluntary contributions to support capacity building and technology transfer among G20 countries and to other countries on a bilateral and multilateral basis, with assistance from relevant international organizations. These models should include policies and strategies to plan and implement extensive projects, investments, other forms of commercial endeavors, and cooperation in the creation of a shared knowledge base to document case studies, lessons learned, and experience dealing with uncertainties. The G20 countries with the largest desalination and renewable energy capacities may sign a Cooperative Framework Agreement to establish the global cooperation platform. G20 countries have the largest market size and investments in renewable energy sources and sustainable development technologies. As established in the 2017 G20 Hamburg summit, the impact of these countries' policies and practices may have positive spillover effects on the rest of the world.

One method to overcome scaling up and replication challenges is to create a market system with incentives such as those proposed by Zhang et al. (2009) toward investigating opportunities and challenges for the development of renewable energy policy in China. Although the law for renewable energy had been passed in the country, it had only been partially successful in achieving sustainable growth. The authors recommend several policy interventions to accelerate the development of the renewable energy sector including clarifying the process management to ensure that policies are fully implemented, and structuring a market investment and financing system that allows entrepreneurs to receive bank loans.

Another study has also concluded that scaling up renewable energy with desalination requires several governmental incentives such as tax breaks and low-interest loans (Goosen, Mahmoudi, and Ghaffour 2014). These incentives are essential in supporting the commercialization of technology and in ensuring effective replication. Additional policy measures such as tradable energy certificates and other broad-based policies are necessary to encourage technological innovation, which can help compete with fossil fuels.

It is also vital to gradually phase out subsidies for fossil fuel and to tax fossil fuel production in order to lower the extent of environmental damage. Studies have showed that coupling PVRO is a well-developed technology that can expand in the future, much like mobile phones and other technologies that only require a few years to become commercially available. Similar to smart phones, the cost of such systems is expected to drop in the future with continuous improvements and mass production (Hans-Josef 2012).

Among G20 countries, at least eight have measurable water desalination capacities. Ensuring government support may include signing a Cooperative Framework Agreement among these eight countries. The aim of such actionable cooperative agreements is to strategize the planning and processing of replication among these eight G20 countries and to overcome the challenges that accompany PVRO as identified earlier in this document.

The expected high penetration of PVRO will culminate in an integrated distribution system among the eight G20 countries. These countries may sign Cooperative Framework Agreements to devise strategies to deal with emergency support procedures when they encounter high uncertainties related to the interruption of PVRO; plan extensive projects, investments, and other forms of commercial endeavors; and cooperate through research and development for overcoming the above identified challenges (Abdmouleh, Alammari, and Gastli 2015; Gao et al. 2020). The technology, case studies, and lessons learned should be made available to other countries.

## Key Recommendations

- The G20 should include PVRO technology as an innovative solution to complement previous efforts on GIVAR by IEA and IRENA. This option can provide a wider range of countries with low-cost and eco-friendly solutions for the production of fresh water while simultaneously increasing the integration of renewable energy sources into the power grid, thus controlling the unfavorable variability of renewable energy sources, and achieving large reductions in cost and carbon emissions.

- The G20 should institutionalize and incentivize PVRO desalination plants under the G20 framework, as part of its collaborative efforts to support the implementation of the G20 Toolkit of Voluntary Options on Renewable Energy Deployment, and within the available resources including renewable energy technology cost analysis, renewable energy investment risk mitigation mechanisms and structured financing options, and the renewable energy map.

- G20 governments should provide a global cooperation platform for renewable desalination replication models as voluntary contributions to support capacity building and technology transfer both among themselves and to other countries on bilateral and multilateral bases, with assistance from relevant international organizations. These models should include strategies to plan extensive projects, investments, other forms of commercial endeavors, and cooperation for the creation of a shared knowledge base that will document case studies, lessons learned, and experience dealing with uncertainties. The G20 countries with the largest desalination and renewable energy capacities may sign a Cooperative Framework Agreement to initiate a global cooperation platform.

**Disclaimer**

This policy brief was developed and written by the authors and has undergone a peer review process. The views and opinions expressed in this policy brief are those of the authors and do not necessarily reflect the official policy or position of the authors' organizations or the T20 Secretariat.

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# APPENDIX A

**Table 1** demonstrates the potential effectiveness of committing to PVRO systems across the G20 countries. The calculations in this table have been made under some assumptions that are listed under the table.

| Country | Factors | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Desalination Capacity (m3/d) (Global Water Intelligence 2017)** | **Contribution to Global Percentage** | **Energy Consumption (kWh/d) (Kim et al. 2019)** | **$CO_2$ Emissions (tn/d) (Raluy, Serra, and Uche 2006)** | **RO CAPEX (mn $) (Napoli and Rioux 2015** | **PV CAPEX (mn $) (IRENA 2018)** | **Energy Storage CAPEX (mm $) (Napoli and Rioux 2015)** | **Water Storage CAPEX (mn$) (Napoli and Rioux 2015)** | **Cost Reduction (mn$)** | **Emission Reduction (tn/d) (Al-Nory et al. 2014)** |
| Global (International Desalination Association 2020) | 107,000,000.0 | 100.0% | 428,000,000.0 | 190,460.0 | 107,000.0 | 130,968.0 | 1,501,210.0 | 21,400.0 | 1,479,810.0 | 428,000.0 |
| G20 | 52,264,479.6 | 48.8% | 209,057,918.3 | 93,030.8 | 52,264.5 | 63,971.7 | 733,270.6 | 10,452.9 | 722,817.8 | 209,057.9 |
| Saudi Arabia | 16,260,541.2 | 15.2% | 65,042,164.8 | 28,943.8 | 16,260.5 | 19,902.9 | 228,135.4 | 3,252.1 | 224,883.3 | 65,042.2 |
| United States | 13,047,199.8 | 12.2% | 52,188,799.1 | 23,224.0 | 13,047.2 | 15,969.8 | 183,052.2 | 2,609.4 | 180,442.8 | 52,188.8 |
| Australia | 6,341,778.0 | 5.9% | 25,367,112.0 | 11,288.4 | 6,341.8 | 7,762.3 | 88,975.1 | 1,268.4 | 87,706.8 | 25,367.1 |

| Country | Factors: Desalination Capacity (m3/d) (Global Water Intelligence 2017) | Contribution to Global Percentage | Energy Consumption (kWh/d) (Kim et al. 2019) | $CO_2$ Emissions (tn/d) (Raluy, Serra, and Uche 2006) | RO CAPEX (mn $) (Napoli and Rioux 2015 | PV CAPEX (mn $) (IRENA 2018) | Energy Storage CAPEX (mm $) (Napoli and Rioux 2015) | Water Storage CAPEX (mn$) (Napoli and Rioux 2015) | Cost Reduction (mn$) | Emission Reduction (tn/d) (Al-Nory et al. 2014) |
|---|---|---|---|---|---|---|---|---|---|---|
| China | 4,364,891.2 | 4.1% | 17,459,564.6 | 7,769.5 | 4,364.9 | 5,342.6 | 61,239.4 | 873.0 | 60,366.4 | 17,459.6 |
| India | 2,847,610.4 | 2.7% | 11,390,441.4 | 5,068.7 | 2,847.6 | 3,485.5 | 39,952.0 | 569.5 | 39,382.5 | 11,390.4 |
| South Korea | 1,700,559.2 | 1.6% | 6,802,236.8 | 3,027.0 | 1,700.6 | 2,081.5 | 23,858.8 | 340.1 | 23,518.7 | 6,802.2 |
| Japan | 1,619,530.9 | 1.5% | 6,478,123.4 | 2,882.8 | 1,619.5 | 1,982.3 | 22,722.0 | 323.9 | 22,398.1 | 6,478.1 |
| Mexico | 1,017,415.8 | 1.0% | 4,069,663.2 | 1,811.0 | 1,017.4 | 1,245.3 | 14,274.3 | 203.5 | 14,070.9 | 4,069.7 |
| Italy | 873,998.0 | 0.8% | 3,495,992.0 | 1,555.7 | 874.0 | 1,069.8 | 12,262.2 | 174.8 | 12,087.4 | 3,496.0 |
| Turkey | 870,101.0 | 0.8% | 3,480,404.0 | 1,548.8 | 870.1 | 1,065.0 | 12,207.5 | 174.0 | 12,033.5 | 3,480.4 |

| Country | Factors | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Desalination Capacity (m3/d) (Global Water Intelligence 2017) | Contribution to Global Percentage | Energy Consumption (kWh/d) (Kim et al. 2019) | $CO_2$ Emissions (tn/d) (Raluy, Serra, and Uche 2006) | RO CAPEX (mn $) (Napoli and Rioux 2015 | PV CAPEX (mn $) (IRENA 2018) | Energy Storage CAPEX (mm $) (Napoli and Rioux 2015) | Water Storage CAPEX (mn$) (Napoli and Rioux 2015) | Cost Reduction (mn$) | Emission Reduction (tn/d) (Al-Nory et al. 2014) |
| Brazil | 663,072.4 | 0.6% | 2,652,289.6 | 1,180.3 | 663.1 | 811.6 | 9,302.9 | 132.6 | 9,170.3 | 2,652.3 |
| United Kingdom | 646,662.0 | 0.6% | 2,586,648.0 | 1,151.1 | 646.7 | 791.5 | 9,072.7 | 129.3 | 8,943.3 | 2,586.6 |
| South Africa | 601,132.0 | 0.6% | 2,404,528.0 | 1,070.0 | 601.1 | 735.8 | 8,433.9 | 120.2 | 8,313.7 | 2,404.5 |
| Indonesia | 425,926.6 | 0.4% | 1,703,706.4 | 758.1 | 425.9 | 521.3 | 5,975.8 | 85.2 | 5,890.6 | 1,703.7 |
| Germany | 401,846.0 | 0.4% | 1,607,384.0 | 715.3 | 401.8 | 491.9 | 5,637.9 | 80.4 | 5,557.5 | 1,607.4 |
| France | 278,618.0 | 0.3% | 1,114,472.0 | 495.9 | 278.6 | 341.0 | 3,909.0 | 55.7 | 3,853.3 | 1,114.5 |
| Canada | 216,585.3 | 0.2% | 866,341.0 | 385.5 | 216.6 | 265.1 | 3,038.7 | 43.3 | 2,995.4 | 866.3 |

| Country | Factors | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Desalination Capacity (m3/d) (Global Water Intelligence 2017) | Contribution to Global Percentage | Energy Consumption (kWh/d) (Kim et al. 2019) | $CO_2$ Emissions (tn/d) (Raluy, Serra, and Uche 2006) | RO CAPEX (mn $) (Napoli and Rioux 2015 | PV CAPEX (mn $) (IRENA 2018) | Energy Storage CAPEX (mm $) (Napoli and Rioux 2015) | Water Storage CAPEX (mn$) (Napoli and Rioux 2015) | Cost Reduction (mn$) | Emission Reduction (tn/d) (Al-Nory et al. 2014) |
| Argentina | 87,012.0 | 0.1% | 348,048.0 | 154.9 | 87.0 | 106.5 | 1,220.8 | 17.4 | 1,203.4 | 348.0 |
| EU | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available |
| Russia | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available | Not Available |

Table 1. **$CO_2$ Emissions and Cost Reductions Analysis Across G20 Countries upon Committing to PVRO Systems**

Source: **Authors (June 11, 2020).**

Assumptions:

1. Desalination capacity includes all desalination projects in 2017 according to governmental and private sector projects. Offline capacity may also be included (Global Water Intelligence 2017).
2. Energy consumption is calculated assuming that RO technology is used at a specific energy consumption level of 4 kWh/m3 according to the high estimate in Kim et al. (2019).
3. RO process emissions are estimated at 1.78 kg of CO2/m3 according to Raluy, Serra, and Uche (2006).
4. RO CAPEX is estimated at $1000 per m3/d, which is at the low end of the estimation of $900-$1200 provided by Napoli and Rioux (2015).
5. The storage capital cost for sodium sulfur flow batteries is estimated at $6,100/kW with the levelized cost of $350/MWh and 87% depth of discharge according to Napoli and Rioux (2015). The batteries are assumed to store energy for half a day (12 hours).
6. PV CAPEX is estimated at $350/kW, provided by IRENA (2018).
7. Water storage CAPEX is estimated at $200/m3, provided by Napoli and Rioux (2015).
8. Cost reduction is calculated from the difference between energy and water storage costs.
9. Emission reduction is calculated by dropping emissions by 1 kg of CO2 for each cubic meter according to Al-Nory et al. (2014).
10. In this analysis, OPEX is neglected as it comprises only a small percentage of CAPEX in ROPV projects.

However, RO plants are in the range of 3 to 4.5 kWh/m3, depending on conditions and design. Using 4 kWh/m^3 is a reasonable approximation. Nonetheless, one concern is that a number of plants in the GCC (and elsewhere) are older thermal plants running MSF or MED, which means that their energy consumption will be higher (depending on the details of the plant design, etc.). This also means that the energy totals for some countries will be higher. The CO2 emissions will depend on the type of power plant. For instance, India generates a lot of power from coal, which has about twice the level of CO2. Overall, the above calculations are made based on a very relaxed approximation. The main purpose of Table 1 is to show the G20 leaders that even the minimum possible is still very expensive, especially environmentally.

# APPENDIX B

**The sustainability of driving SWRO desalination units with renewable energy sources (PV panels or CSP) faces the following technical challenges.**

1. Local manufacturing: PV panels still require rare earth elements that are mainly available in China. To expand the PV manufacturing industry into other countries, reliance on rare earths should be reduced through further research on PV materials.
2. Energy conversion efficiency: PV panels are characterized by relatively low electrical-conversion efficiency for affordably priced units. Additional funding is necessary for the development of more efficient PV systems at a commercial scale and a low cost.
3. Environmental durability: PV systems' efficiency decreases when panels heat up, or when surfaces are affected by dust, sandstorms, and humidity. Research support is necessary to improve the characteristics of PV panel surfaces in order to repel dust and to enable low-cost robotic cleaning.
4. Energy storage: Storage remains a major challenge that raises the capital cost of renewable desalination systems. The current cost of levelized electricity from PV systems with mechanical energy storage is estimated at about 0.078 $/kWh. Reducing this cost will directly reduce PV-RO water desalination energy costs. Research and development are necessary for efficient, cost-effective energy storage, both for the development of better batteries and for innovative mechanical energy storage systems. The latter include pumped hydro (suitable for some topographies, but with relative high losses) and large-scale block stacking strategies, as in the Energy Vault technology.
5. Improved membranes: Membrane replacement accounts for almost 20% of the annual RO OPEX. Additionally, membrane fouling contributes toward incremental energy consumption over the life of a plant. Research should thus focus on improving membrane resilience and modifying surface characteristics in order to decrease fouling propensity (Okamoto and Lienhard 2019). Better membrane cleaning strategies are also necessary, particularly involving rapid chemical-free technologies.
6. Dynamic pretreatment: The effective pretreatment of RO systems that are rapidly responsive to changing or location-specific water quality that varies from one region to another is necessary. For example, a major concern is ensuring that plants continue operating during algal blooms but attaching a rarely used DOF pretreatment system adds substantial capex. Thus, the development of real-time, adjustable, cost-effective, and low energy consumption pretreatment technologies is necessary.

7. Capital cost reduction for CSP: CSP can be coupled with molten-salt energy storage to provide either a baseload or a dispatchable energy production system. CSP can drive RO and multi-effect distillation desalination systems. A key development that is necessary in this area is additional engineering to reduce capex. The use of high temperature thermal batteries should be explored as a component of CSP-desalination systems. Thermal batteries enable dispatchable electricity production (Amy et al. 2019) that is well-suited to driving RO.
8. Brine management and valorization: All current desalination processes produce concentrated brine as a by-product. Further research is needed on the recovery of valuable minerals and chemicals from brine (Kumar et al. 2019a, 2019b). Monitoring and policy measures are necessary in some locations to ensure that brine is sufficiently diluted when it is discharged into the sea, so that the marine environment is protected.

In summary, the technology for large-scale, renewable-energy-driven desalination deployment currently exists. Further research and development are necessary from governments in order to take on the challenges mentioned above so that renewable desalination will cost less, be available widely, and be environmentally benign.

# APPENDIX C

Figure 2. **PV Solar Energy with RO has been implemented since 2016 in Khafji, Saudi Arabia. The KACST project has a capacity of 60,000 $m^3$/day**

Figure 3. **PV Solar Energy with RO has been implemented in since 2016 in Farasan Island, Saudi Arabia through the Solar Desalination project**

# AUTHORS

**Malak Al-Nory**
Effat University

**Mohammed Antar**
King Fahd University of Petroleum and Minerals

**Alexander Brodsky**
George Mason University

**Stephen Graves**
Massachusetts Institute of Technology

**Hussameldin Khonkar**
King Abdulaziz City for Science and Technology

**John Lienhard**
Massachusetts Institute of Technology

**Khulood Rambo**
Effat University

**Sa'd Shannak**
Texas A&M