

MESSAGEix MODEL FOR MALDIVES CAPITAL MALÉ

ABBREVIATIONS

| | |
|------|--|
| AC | Air conditioning |
| SWAC | Seawater air conditioning |
| RO | Reverse osmosis desalination |
| DSCD | Deep seawater cooling and desalination |

1 TECHNOLOGIES INTRODUCTION

Based on the article wrote by Julian, in this section the main characteristics of the cooling and desalination technologies applied in the Malé's MESSAGEix model are going to be explained in a synthesized way. The applied technologies were: Air-conditioning (AC); Seawater air conditioning (SWAC); Reverse Osmosis desalination (RO); and, Deep seawater cooling and desalination (DSCD).

AC technologies considered in this model were chillers, used in conventional AC systems. SWAC is a district cooling technology that uses deep cold seawater for cooling. SWAC replaces the AC systems, greatly reducing the electricity consumption and costs of cooling. SWAC systems power savings can approach 80% compared to conventional chillers. The main disadvantage of such a system lies in its high initial investment requirement.

RO consist of the desalination of the seawater with reverse osmosis membrane. RO is considered the most energy efficient and cost-effective alternative for desalination. RO systems, with capital costs around 800 thousand dollars, are cheaper. However, it should be noted that as 1.000 m³/day is a relatively small amount of water production.

DSCD consist of the desalination of the warm superficial seawater with reverse osmosis membrane, followed by cooling of the desalinated water with seawater air-conditioning and the distribution of the cold water for both cooling and water supply services (Figure 1). The cooling services must be provided prior to the water supply, as the water is the cooling medium required for the cooling service. After the cooling service is provided, the temperature of the water will reach close to ambient temperature and the water can be supplied for other customers.

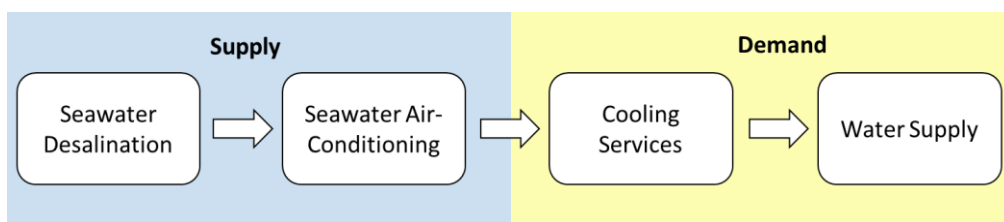


Figure 1 - Deep seawater cooling and desalination description diagram.

The superficial water should be used for desalination. This is because the efficiency and desalination capacity of a reverse osmosis (RO) systems is directly impacted by the temperature of the water.

1.1 DSCD Potential and Malé's Case Study

An important aspect of DSCD plants is the balance between the cooling and water supply services that the system provides and the energy consumption of the system. For example, to

desalinate 1 m³/s of seawater, around 10 MWe of electricity is required. This flow of cold fresh water produced from the DSCD plant has the cooling potential of 82 MW_t, which could replace an air-conditioning system that requires 20 MWe. Table 1 shows the amount of cooling energy potential in the deep ocean seawater.

Table 1 - Deep ocean seawater potential

| | Technology | Driving force | Quantity | Electricity generation or consumption | Cooling potential |
|------|--|--|--|---------------------------------------|--|
| DSCD | Seawater Desalination with Reverse-Osmosis | Electricity | Desalinated water: 1 m ³ /s | -10 MW _e | - |
| | Deep Seawater | Temperature difference: $\Delta T = 20^{\circ}\text{C}$ | Deep seawater flow: 1 m ³ /s | -2 MW _e | $20^{\circ}\text{C} \times 4.0 \text{ kJ/kg.K}^i \times 1 \text{ m}^3/\text{s} \times 1028 \text{ kg/m}^{3ii}$ = 82 MW _t |

1.1 Malé's freshwater and cooling demand

Malé is one of the most densely populated locations on the world with a population of 133,412 people in an area of 1.95 km² and relies on seawater desalination to meet almost all its water supply. This amounts to around 80,000 m³/d, that is equivalent to around 1 m³/s. As Malé is the capital of the Maldives it also provides water supply to some of its 1190 islands. Total freshwater withdrawal by the Maldives islands is estimated at only 27,400 m³/d.

The electricity demand, for the year 2017, in Malé was about 306 GWh in which 30% was used to attend the cooling demand (Hillendahl et al., 2017). The others demand for electricity were: appliances (48%), lighting (16%), and cooking (5%) (Figure 2).

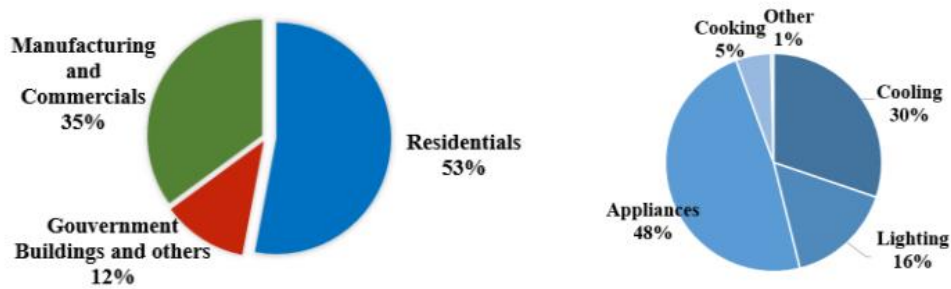


Figure 2 – Electricity demand distribution (Left) and electricity demand distribution in residential sector (right) in Malé. Source: (Hillendahl et al., 2017).

2 MESSAGEix METHODOLOGY

The main idea is to simulate the electricity system of Malé up to 2040 considering the actual system in the year 2020. It was considered that in 2020, 95% of electricity were provided by oil power plants and 5% by solar photovoltaic power plants, 100% of the fresh water were provided by reverse osmosis desalination, and 100% of the cooling demand were provided by air conditioning systems. Then, propose a horizon scenario up to 2040 in which the cooling demand will be supplied by 50% AC, 20% DSCD and 30% SWAC (Figures 3). Desalination will be supplied by 30% RO and 70% DSCD (Figure 4). And, electricity will be supplied by 70% of solar photovoltaic power plants and batteries, and 30% with oil power plants (Figure 5).

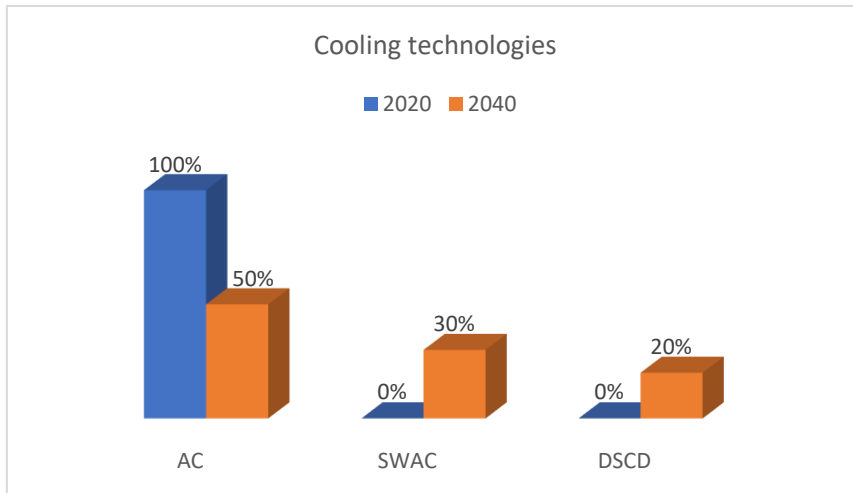


Figure 3 – Scenarios for 2020 and 2040 for each cooling technology.

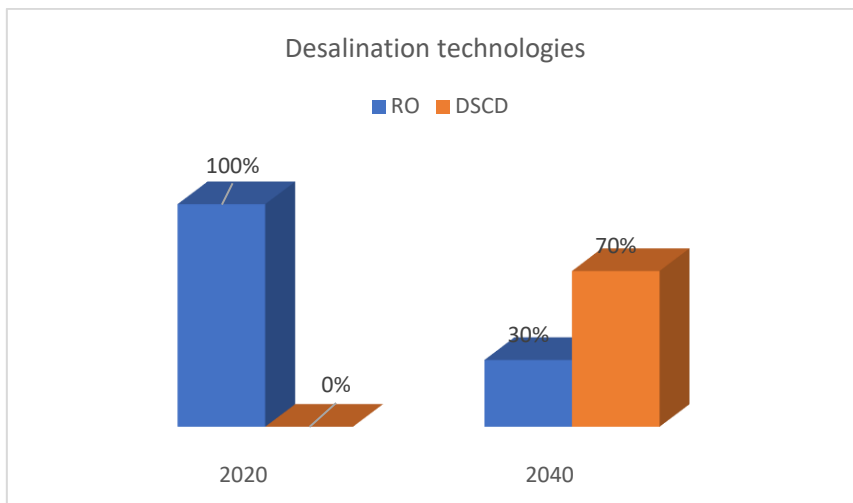


Figure 4 - Scenarios for 2020 and 2040 for each desalination technology.

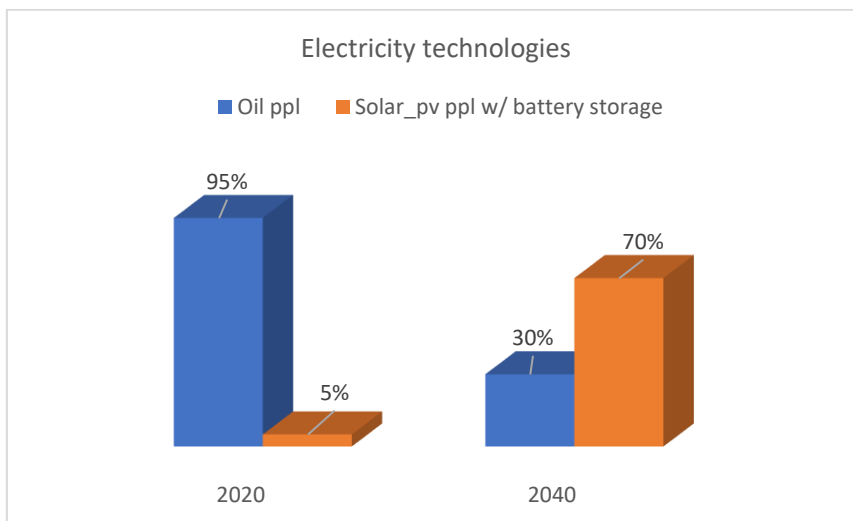


Figure 5 - Scenarios for 2020 and 2040 for each electricity technology.

To do so, the proposed methodology considered 3 input resources (solar, oil, and seawater), 3 secondary technologies in order to transform the resources into electricity (solar photovoltaic,

oil, and batteries), and 1 reverse osmosis desalination plant to transform seawater into fresh water. The final use technologies to supply the required cooling, freshwater, and electricity demand were: AC, SWAC, RO, DSCD (Figure 6).

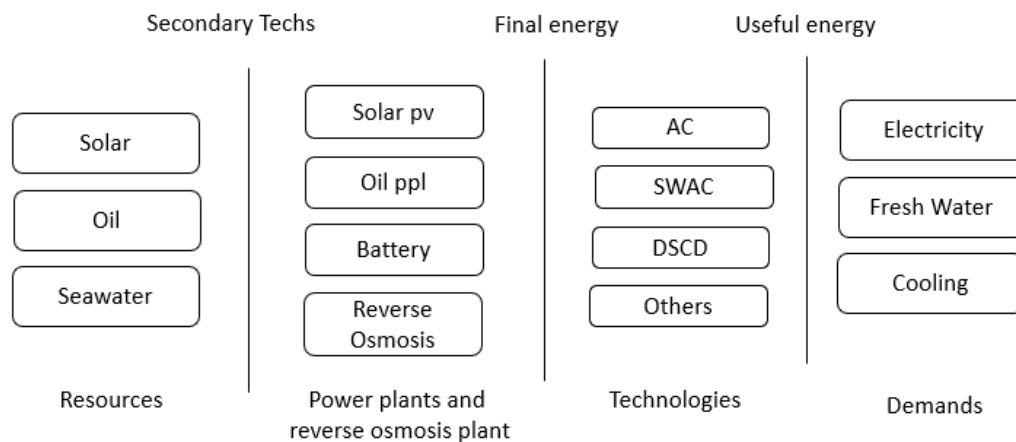


Figure 6 – MESSAGEix methodology framework

2.1 Growth estimation

Growth estimation were based on the forecast of Hillendahl et al., 2017.

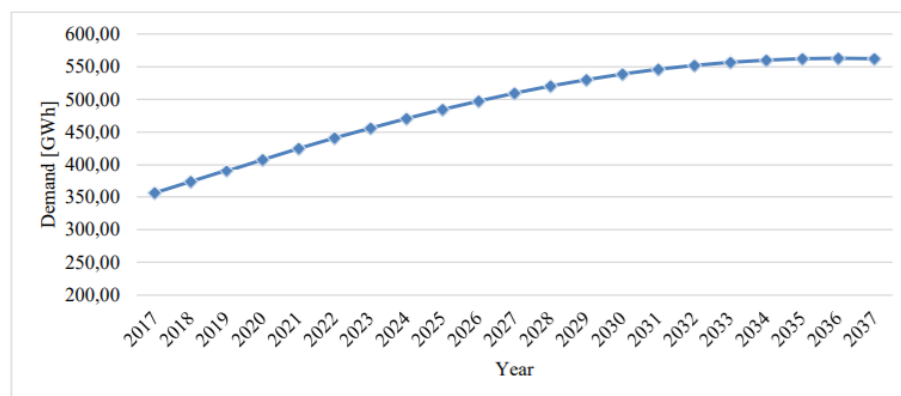


Figure 7 – Forecast for electricity demand on Malé until 2037. Source: (Hillendahl et al., 2017).

2.2 Demand for electricity, cooling and freshwater

In the MESSAGEix the electricity demand for electricity were divided in two. One to attend the the cooling demand and other for the others types of demand showed in Figure 2. In this case, was considered that the cooling demand is 30% of the total electricity demand in multiplied by 3 to obtain the demand in thermal megawatt (Table 1).

Table 1 – Annual cooling demand in thermal megawatt for Malé from 2025 up to 2040.

| | node | commodity | level | year | time | value | unit |
|------|----------|-----------|--------|------|------|-----------|------|
| 2025 | Maldives | cooling | useful | 2025 | year | 50.930137 | MWta |
| 2030 | Maldives | cooling | useful | 2030 | year | 55.960274 | MWta |
| 2035 | Maldives | cooling | useful | 2035 | year | 57.217808 | MWta |
| 2040 | Maldives | cooling | useful | 2040 | year | 57.846575 | MWta |

Then, 70% of the electricity demand were defined for the appliances, cooking and lighting, which configure the others demand for electricity (Table 2).

Table 2 – Annual electricity demand for appliances, cooking and lighting in Malé from 2025 up to 2040.

| | node | commodity | level | year | time | value | unit |
|------|----------|-------------|-------|------|------|-----------|------|
| 2025 | Maldives | electricity | final | 2025 | year | 39.612329 | MWta |
| 2030 | Maldives | electricity | final | 2030 | year | 43.524658 | MWta |
| 2035 | Maldives | electricity | final | 2035 | year | 44.502740 | MWta |
| 2040 | Maldives | electricity | final | 2040 | year | 44.991781 | MWta |

In the sequence, the demand for fresh water in Malé was defined based on IRENA (2015) data: which amounts to around 80,000 m³/d, that is equivalent to around 1 m³/s. Thus, the annual freshwater demand is 80,000 multiply by 365 (Table 3).

Table 3 – Annual Freshwater demand for Malé from 2025 up to 2040.

| | node | commodity | level | year | time | value | unit |
|---|----------|------------|--------|------|------|----------|------------------|
| 0 | Maldives | freshwater | useful | 2025 | year | 29200000 | m ³ a |
| 1 | Maldives | freshwater | useful | 2030 | year | 29200000 | m ³ a |
| 2 | Maldives | freshwater | useful | 2035 | year | 29200000 | m ³ a |
| 3 | Maldives | freshwater | useful | 2040 | year | 29200000 | m ³ a |

2.3 Engineering Parameters

Table 4 resumes the input and outputs defined for the applied technologies in the Maldives model.

Table 4 – Input and output parameters for applied technologies

| Application | Technology | Input/output ratio |
|-------------|------------|----------------------------------|
| Cooling | AC | Output: 3 MWta |
| | | Input: 1 MWa |
| | SWAC | Output: 20 MWta |
| | | Input: 1 MWa |
| | DSCD | Output: 40 MWta |
| | | Input: 1 MWa |
| | RO | Output: 3.100.000 m ³ |

| | | |
|-------------|----------|----------------------------------|
| Fresh Water | DSCD | Input: 1 MWa |
| | | Output: 3.100.000 m ³ |
| Electricity | Oil | Input: 1 MWa |
| | | Output: 1 MWa |
| | Solar pv | Output: 1 MWa |
| | Battery | Output: 1 MWa |

2.4 Operational Constraints and Parameters

Table 5 resumes the operational constraints and parameters defined for the applied technologies in the Maldives model.

Table 5 – Operational constraints and parameters of applied technologies

| Application | Technology | Capacity Factor | Lifetime (years) |
|-------------|------------|-----------------|------------------|
| Cooling | AC | 0.3 | 15 |
| | SWAC | 0.8 | 20 |
| | DSCD | 0.8 | 20 |
| Fresh Water | RO | 0.8 | 20 |
| | DSCD | 0.8 | 20 |
| Electricity | Oil | 0.75 | 30 |
| | Solar pv | 0.3 | 20 |
| | Battery | 0.3 | 5 |

2.5 Technological Diffusion and Contraction

As mention in the introduction the idea is to simulate a transition of the electricity, cooling and desalination systems of Malé from the actual baseline scenario to a scenario with more efficiency technologies and renewable sources (Figures 3 to 5).

In MESSAGEix it was defined the parameters: **‘historical_activity’** and **‘initial_activity_up’** with the share of technologies defined for the year 2020 scenario. Next, to introduce the share of technologies of the 2040 scenario it was defined the parameter **‘bound_new_capacity_up’** with the new values.

2.6 Technoeconomic Parameters

2.6.1 Investment cost

In this model, the SWAC project costs was based on the CAPEX determined by DEVCCO (2016). So, the investment cost for SWAC projects in USD/kW were 768.

| CAPEX | | Hulhumale' |
|------------------------------|------|------------|
| Production | | 100 MW |
| | | SWAC |
| District Cooling Plant (DCP) | kUSD | 34,410 |
| Sea Water System (SWS) | kUSD | 42,438 |
| Total Production system | kUSD | 76,848 |

Figure 8 - Capex breakdown on main SWAC system parts. Source: (DEVCCO, 2016).

Reverse Osmosis investment cost was based on the ADVISIAN (2020) report (Figure 9). So, based on Figure 9 the cost considered for 80,000 m³/d were 0.95 U\$/m³.

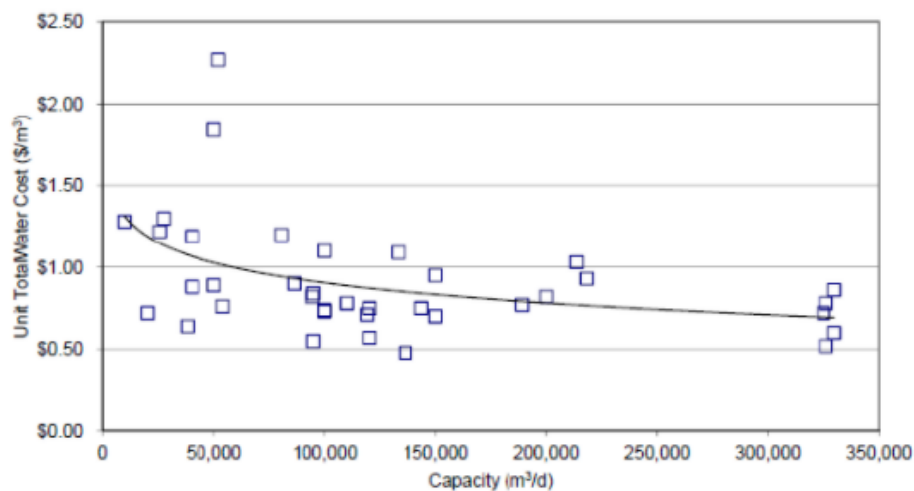


Figure 9 - RO plant unit production cost vs. project capacity. Source: (ADVISIAN, 2020).

Thus, the cost for DSCD considered were equal to the cost of RO plus the cost of SWAC multiply by 0.7.

In the case of solar photovoltaic it was considered 677 U\$/kW based on the IEA (2019) data for India (Figure 10).

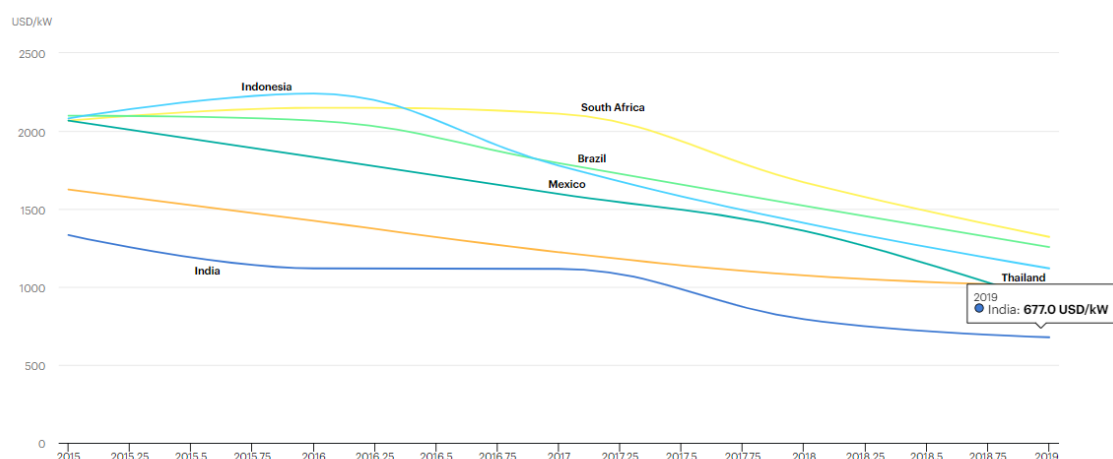


Figure 10 - Capital costs of utility-scale solar PV in selected emerging economies. Source: (IEA, 2020)

Office buildings using two-pipe HVAC systems will cost U\$15 to U\$23 per square foot (AirFixture, 2020). According to EIA (2015) the average size of commercial buildings are 19,000 square feet. Then, the following procedure was done to estimate the investment cost for each kW:

1. Divide the space's square footage by 500;
2. Multiply the number from step 1 by 12,000. This is the number of Btu your system will need to remove to cool the space;
3. Add 380 Btu for each person who works in the space;
4. For each window in the space add 1,000 Btu. For each kitchen, add 1,200 Btu.

Thus, the investment cost of HVAC systems considered for Malé were: 880/kW.

The costs for the others technologies as batteries were based on the MESSAGEix-Brazil model value for stor_ppl. For oil power plant CAPEX values were obtain from the MESSAGEix Austria baseline model.

2.6.2 Base fixed cost

OPEX for SWAC was as well based on DEVCCO (2016) report (Figure 11).

| OPEX | | Hulhumale' |
|----------------|-----------|------------|
| | | 100 MW |
| | | SWAC |
| Administrative | kUSD/year | 1,750 |
| Electricity | kUSD/year | 16,408 |
| O&M | kUSD/year | 1,392 |
| Total opex | kUSD/year | 19,549 |

Figure 11 - Opex breakdown on main SWAC system parts. Source: (DEVCCO, 2016).

OPEX price for RO were based on ADVISIAN (2020) report. The base fixed cost for the others technologies, battey_ppl, and solar_pv_ppl, were based on the MESSAGEix-Brazil model. For oil power plant OPEX values were obtain from the MESSAGEix Austria baseline model.

2.6.3. Base variable cost

In this case for oil power plant the value was obtained from the MESSAGEix Austria baseline model. For the others technologies, battey_ppl, and solar_pv_ppl, were based on the MESSAGEix-Brazil model. Cooling and desalination technologies were considered to have zero variable costs.

3. RESULTS

Figure 12, 13, and 14 show the amount of energy (electricity, cooling and seawater) delivered by each technology. Figure 12 shows that the solar production increase over time, from 18,85% in 2025 to 32.70% in 2040.

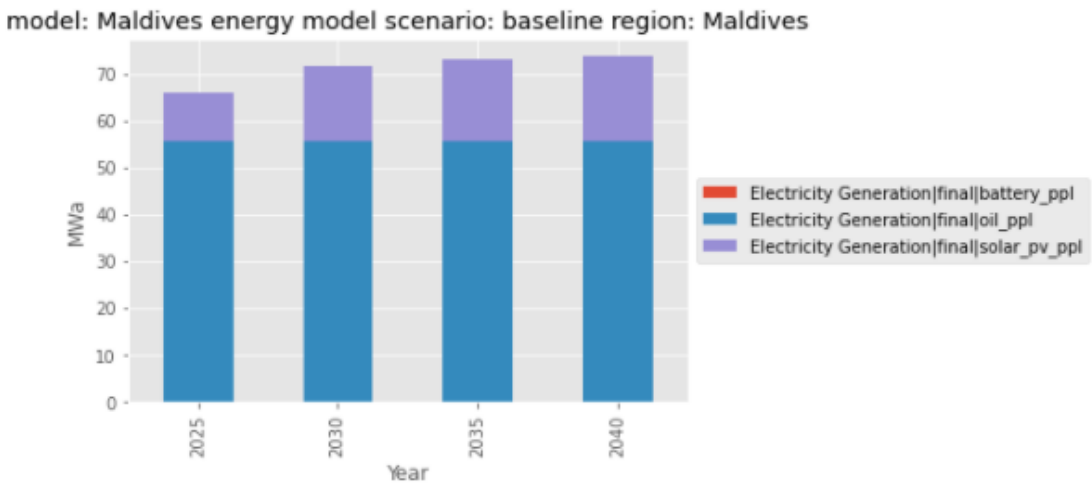


Figure 12 – Final energy generation by secondary technologies.

The cooling demand was supplied only by air conditioning technology.

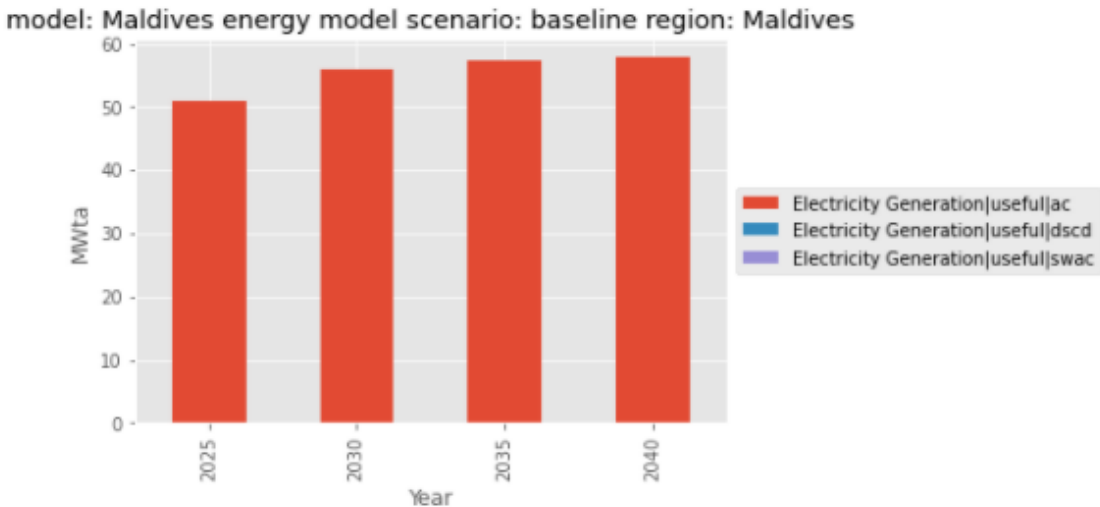


Figure 13 – Final energy consumed by final use technologies to supply the cooling demand.

Also, the model optimized only a technology to produce the demand for freshwater which was the reverse osmosis plant.

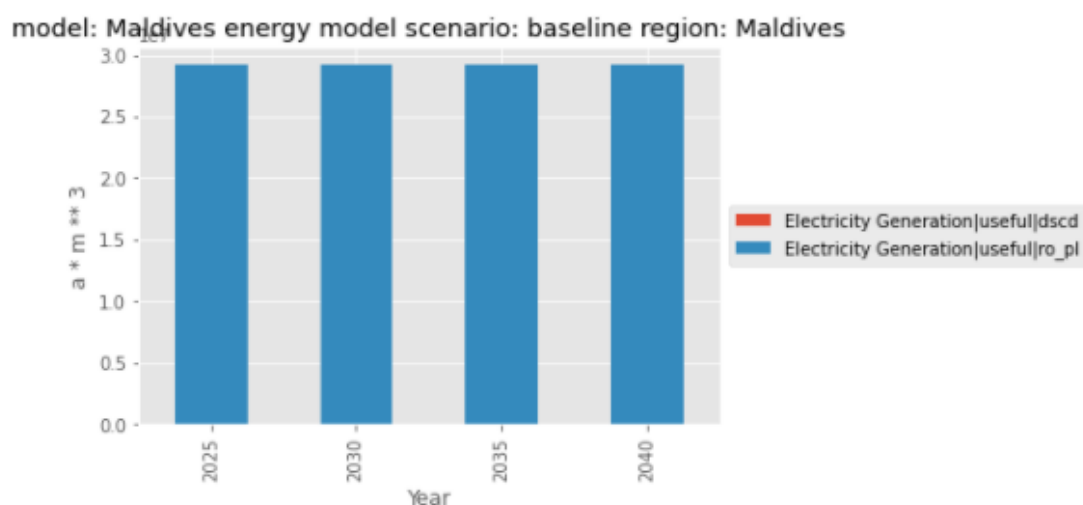


Figure 14 - Final energy consumed by final use technologies to supply the fresh water demand.

4. ANALYSIS OF RESULTS

Table 6 shows that the amount of energy produced by secondary sources or consumed by the final use technologies are equivalent to the energy demand of each commodity. So, the model was able to simulate the supply and demand of each commodity with precision.

Table 6 – Energy demand and consumed by each commodity

| | 2025 | 2030 | 2035 | 2040 |
|---|------------|------------|------------|------------|
| cooling demand (MWta) | 50.9 | 56.0 | 57.2 | 57.8 |
| cooling consumed (MWta) | 50.9 | 56.0 | 57.2 | 57.8 |
| electricity demand (MWa) | 66.0 | 71.6 | 73.0 | 73.7 |
| electricity produced (MWa) | 66.0 | 71.6 | 73.0 | 73.7 |
| fresh water demand (m ³ a) | 29,200,000 | 29,200,000 | 29,200,000 | 29,200,000 |
| fresh water produced (m ³ a) | 29,200,000 | 29,200,000 | 29,200,000 | 29,200,000 |

4. DIFFICULTIES TO OVERCOME

What I have not yet managed to develop in this model was to define the initial (year 2020) and final technology portfolio for the 2040 scenario. Even though, I add the **‘historical_activity’** and **‘initial_activity_up’** parameters the model’s results didn’t follow this specification.

In another attempt I created another scenario: 'share_constraint' with the objective of define the share of technologies for each commodity for the year 2040, but the results were the same as the baseline scenario. So, what can I do to overcome this issue?

I’m currently working on the storage model.

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