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 m^3/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 suppled for other customers.

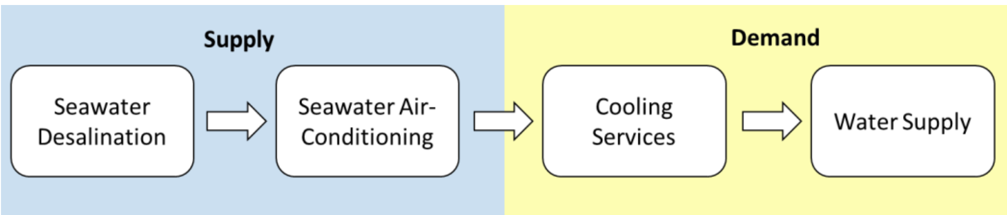

Figure 1 - Deep seawater cooling and desalination description diagram.

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 m^3/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 MWt, 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: $\Delta T = 20^oC$	Deep seawater flow: 1 m^3/s	-2 MW_e	20^oC x 4.0 kJ/kg.K[i] x 1 m^3/s x 1028 kg/m^3[ii] = 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 km^2 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 m^3/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).

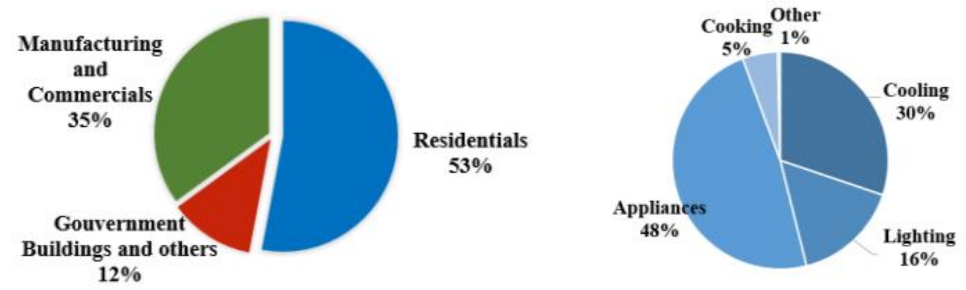

Figure 2 – Electricity demand distribution (Left) and electricity demand distribution in residential sector (right) in Malé. Source: (Hillendahl et al., 2017).

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).

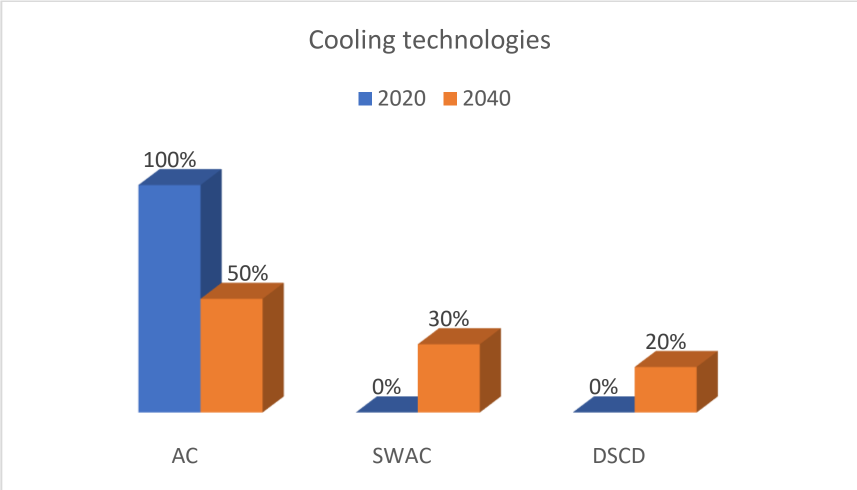

Figure 3 – Scenarios for 2020 and 2040 for each cooling technology.

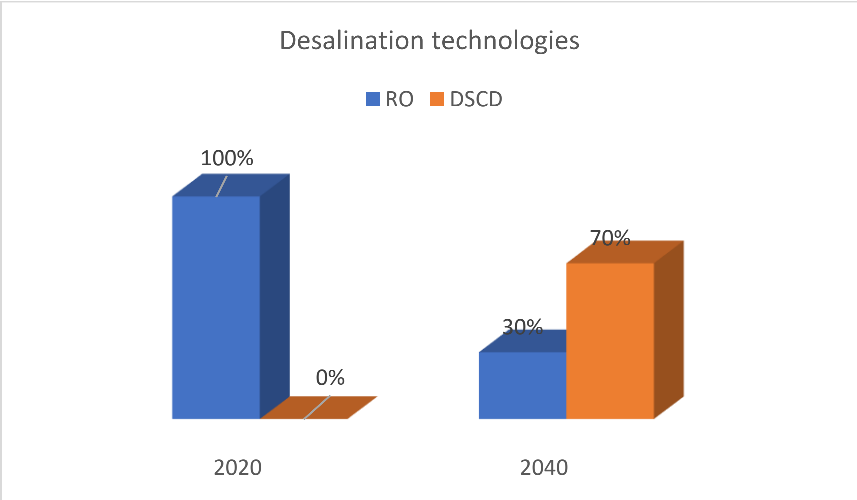

Figure 4 - Scenarios for 2020 and 2040 for each desalination technology.

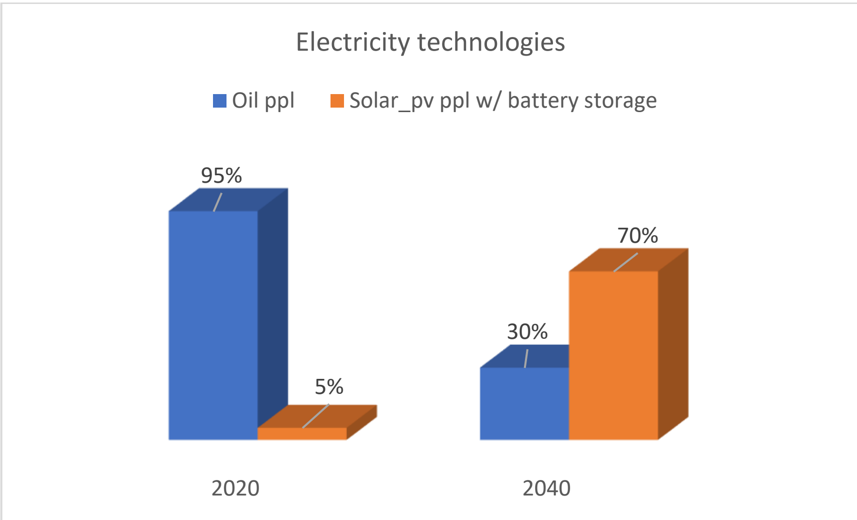

Figure 5 - Scenarios for 2020 and 2040 for each electricity technology.

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).

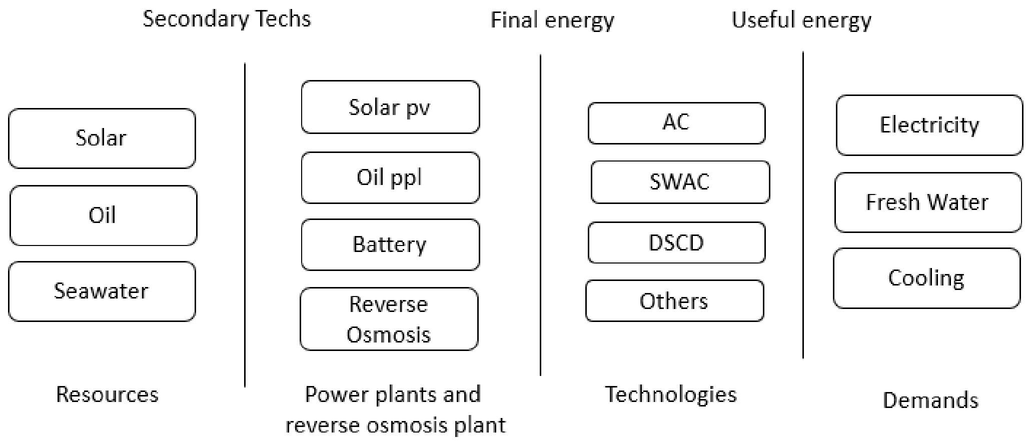

Figure 6 – MESSAGEix methodology framework

2.1 Growth estimation

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

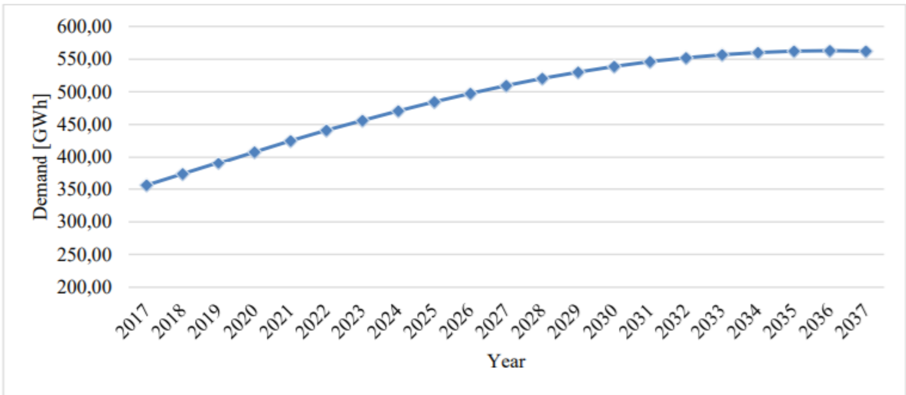

Figure 7 – Forecast for electricity demand on Malé until 2037. Source: (Hillendahl et al., 2017).

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	444150.0	MWta
2030	Maldives	cooling	useful	2030	year	484785.0	MWta
2035	Maldives	cooling	useful	2035	year	504630.0	MWta
2040	Maldives	cooling	useful	2040	year	511245.0	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 2040.

	node	commodity	level	year	time	value	unit
2025	Maldives	electricity	final	2025	year	345450.0	MWa
2030	Maldives	electricity	final	2030	year	377055.0	MWa
2035	Maldives	electricity	final	2035	year	392490.0	MWa
2040	Maldives	electricity	final	2040	year	397635.0	MWa

In the sequence, the demand for fresh water in Malé was defined based on IRENA (2015) data: which amounts to around 80,000 m^3/d, that is equivalent to around 1 m^3/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^3a
1	Maldives	freshwater	useful	2030	year	29200000	m^3a
2	Maldives	freshwater	useful	2035	year	29200000	m^3a
3	Maldives	freshwater	useful	2040	year	29200000	m^3a

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

<table>
<tr><th>Application</th><th>Technology</th><th>Input/output ratio</th></tr>
<tr><td rowspan="6">Cooling</td><td rowspan="2">AC</td><td>Output: 3 MWta</td></tr>
<tr><td>Input: 1 MWa</td></tr>
<tr><td rowspan="2">SWAC</td><td>Output: 20 MWta</td></tr>
<tr><td>Input: 1 MWa</td></tr>
<tr><td rowspan="2">DSCD</td><td>Output: 40 MWta</td></tr>
<tr><td>Input: 1 MWa</td></tr>
<tr><td></td><td>RO</td><td>Output: 3.100.000 m^3</td></tr>
</table>

Fresh Water		Input: 1 MWa
	DSCD	Output: 3.100.000 m³
		Input: 1 MWa
Electricity	Oil	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 Production		Hulhumale' 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.

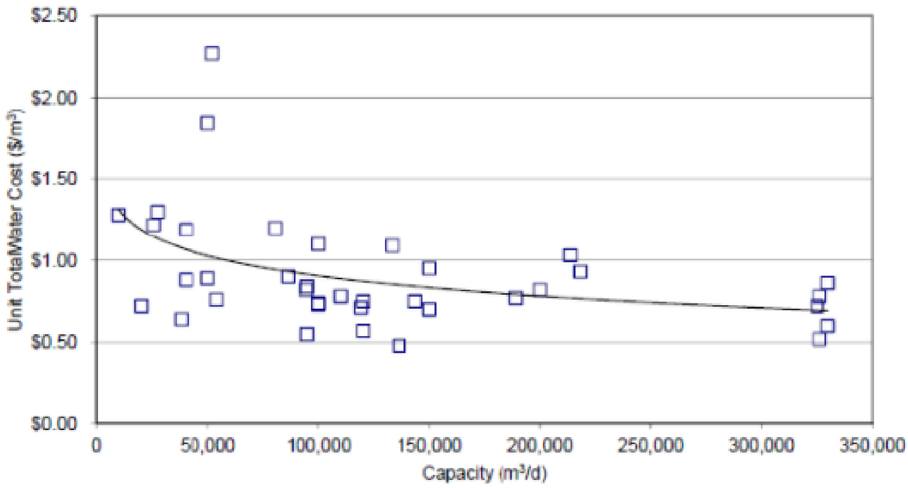

Figure 9 - RO plant unit production cost vs. project capacity. Source: (ADVISIAN, 2020).

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$D/kW based on the IEA (2019) data for India (Figure 10).

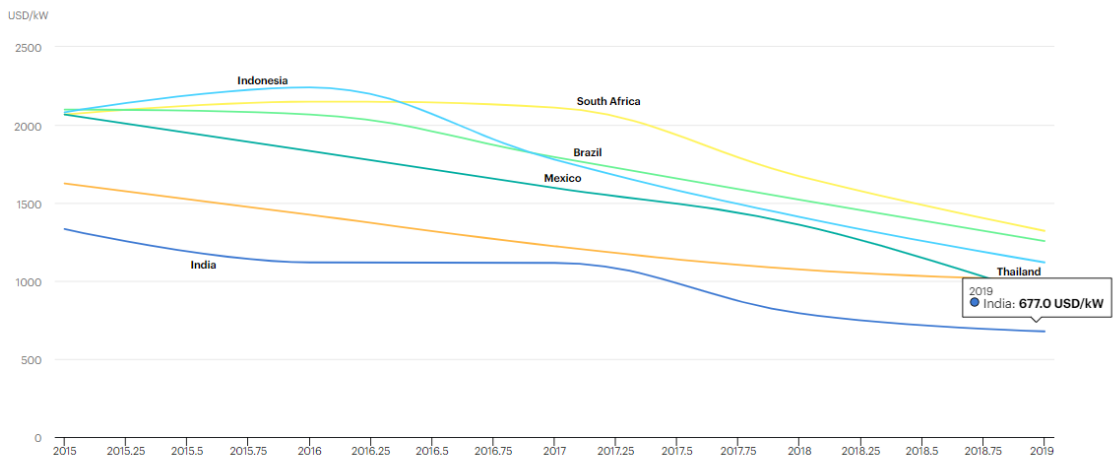

Figure 10 - Capital costs of utility-scale solar PV in selected emerging economies. Source: (IEA, 2020)

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 34% in 2025 to 43% in 2040.

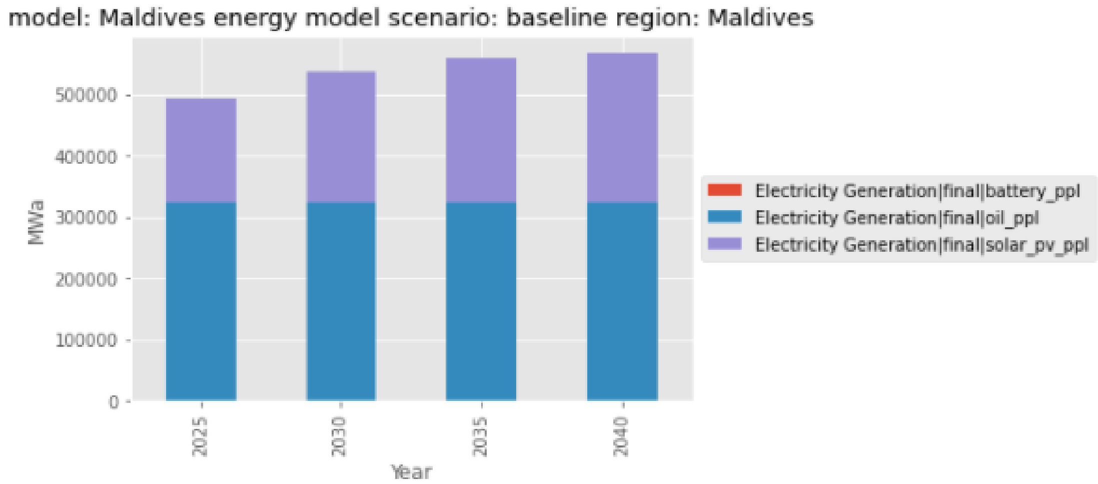

Figure 12 – Final energy generation by secondary technologies.

The cooling demand was supplied only by air conditioning technology.

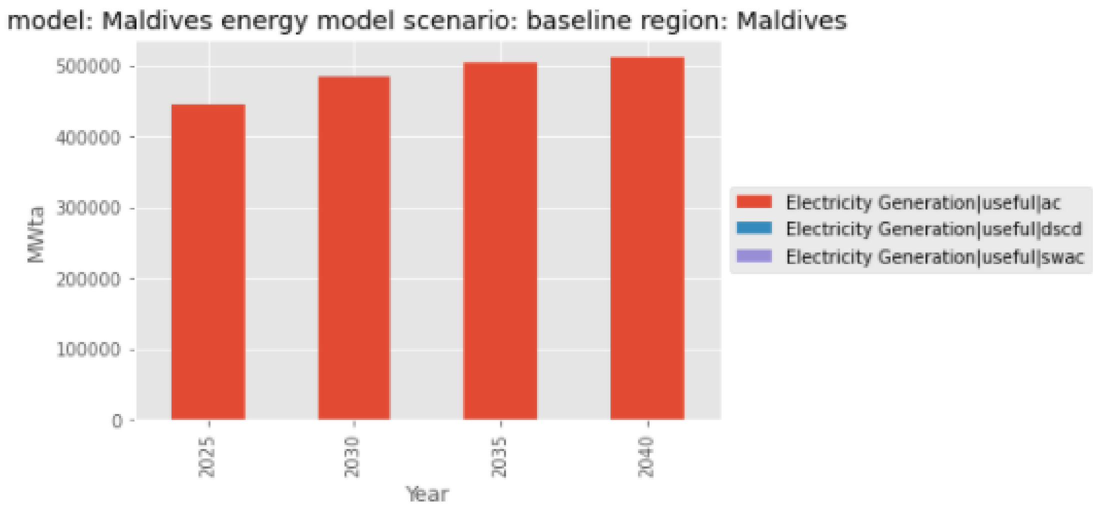

Figure 13 – Final energy consumed by final use technologies to supply the cooling demand.

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

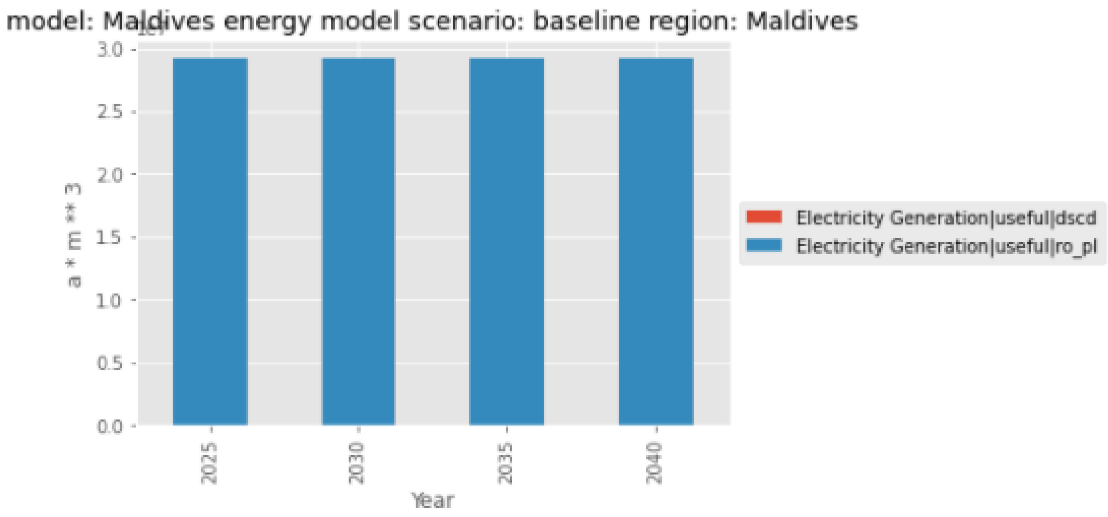

Figure 14 - Final energy consumed by final use technologies to supply the fresh water demand.

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	444,150	484,785	504,630	511,245
cooling consumed	444,150	484,785	504,630	511,245
electricity demand	493,500	538,650	560,700	568,050
electricity produced	493,509	538,659	560,709	568,059
fresh water demand	29,200,000	29,200,000	29,200,000	29,200,000
fresh water produced	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?

Also, I wasn´t able to apply the storage technology.

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