DATA ANNEX: "Modeling policy pathways to maximize renewable energy growth and investment in Democratic Republic of the Congo using OSeMOSYS"

1. MODELING ASSUMPTIONS

A critical component of this study is the use of the Open Source Energy Modelling System (OSeMOSYS), which is a bottom-up energy systems optimization model that is useful for energy infrastructure planning at a country, regional, or global level. Fundamental to OSeMOSYS is its optimization objective to generate the lowest net present cost energy system to meet endogenously defined demand for a geography. Unique modeling scenarios can be specified using researcher-defined energy generation technologies and by inputting cost, activity, capacity, and/or emissions constraints that the model must obey (Howells et al., 2011). In an effort to make this study as practical as possible and to allow it to serve as an input for future research, emphasis was put on ensuring data retrievability; model reusability, repeatability, reconstructability, and interoperability; and overall auditability, recommended by (Howells et al., 2021) as best practices in energy modeling for policy support.

See Table A1 for descriptions of all technologies included in the OSeMOSYS model for this study. For parameter data values not mentioned explicitly in this document, values from (Cannone et al., 2021) were used. An overview of relevant OSeMOSYS parameters is provided in Table A2.

1.1 Electricity Demand Profile

Energy demands on the grid fluctuate from moment to moment, but to better represent temporal demand, country data can be aggregated by the hour. For DRC, the most recent hourly demand dataset identified is based on calendar year 2015 and was extracted from the PLEXOS-World dataset, which provides country-specific energy data (Brinkerink, Gallachóir and Deane, 2021).

Demands are assumed to be for electricity consumption within DRC and do not include additional demands for electricity export. For this study, the year was segmented into four seasons (S1 from December to February, S2 from March to May, S3 from June to August, and S4 from September to November) and two dayparts (D1 “day” from 07:00-19:00 and D2 “night” from 19:00-07:00 West African Standard Time). Thus, the four seasons and two dayparts combine to form eight timeslices.

Figure 1. *(a) 2015 hourly demand versus the timeslice average for D1 “day” hours and (b) D2 “night” hours for all four seasons in DRC, adapted from (Brinkerink and Deane, 2020)* shows the average annual demand by timeslice for both dayparts in comparison to the annual demand data. Reasonable model solve times and the overall shape of the annual demand profile matching the timeslice averages justify the use of eight timeslices. In addition, for some technologies, data inputs such as capacity factors were not available at more specific time granularities, so using more than eight timeslices would have introduced unnecessary model complexity. It is important to note that the consolidation of a year into timeslices is a simplification of reality, which is true of all models.

The Electricity Model Base for Africa (TEMBA) reference dataset (Pappis et al., 2021) was used to set the annual industrial, residential, and commercial electricity demand for DRC (using the “SpecifiedAnnualDemand” parameter in OSeMOSYS). The selected model period for this study was set as 2021-2070. DRC-specific data from the Global Electrification Platform (GEP) (2020) provided a projection for the annual least cost on-grid and off-grid generation, assuming 100% electrification by 2030. For the purposes of this study, the GEP split was used from 2021 through 2030, the last year of projection. In all subsequent years, the 2030 split was used (i.e., ~59% on-grid generation and ~41% off-grid generation) (see Figure 2). This assumption is a known limitation because the on/off-grid split is likely to change beyond 2030, but no other data sources were found to inform alternate ratios. The final energy demands used in this study are summarized in Table A8.

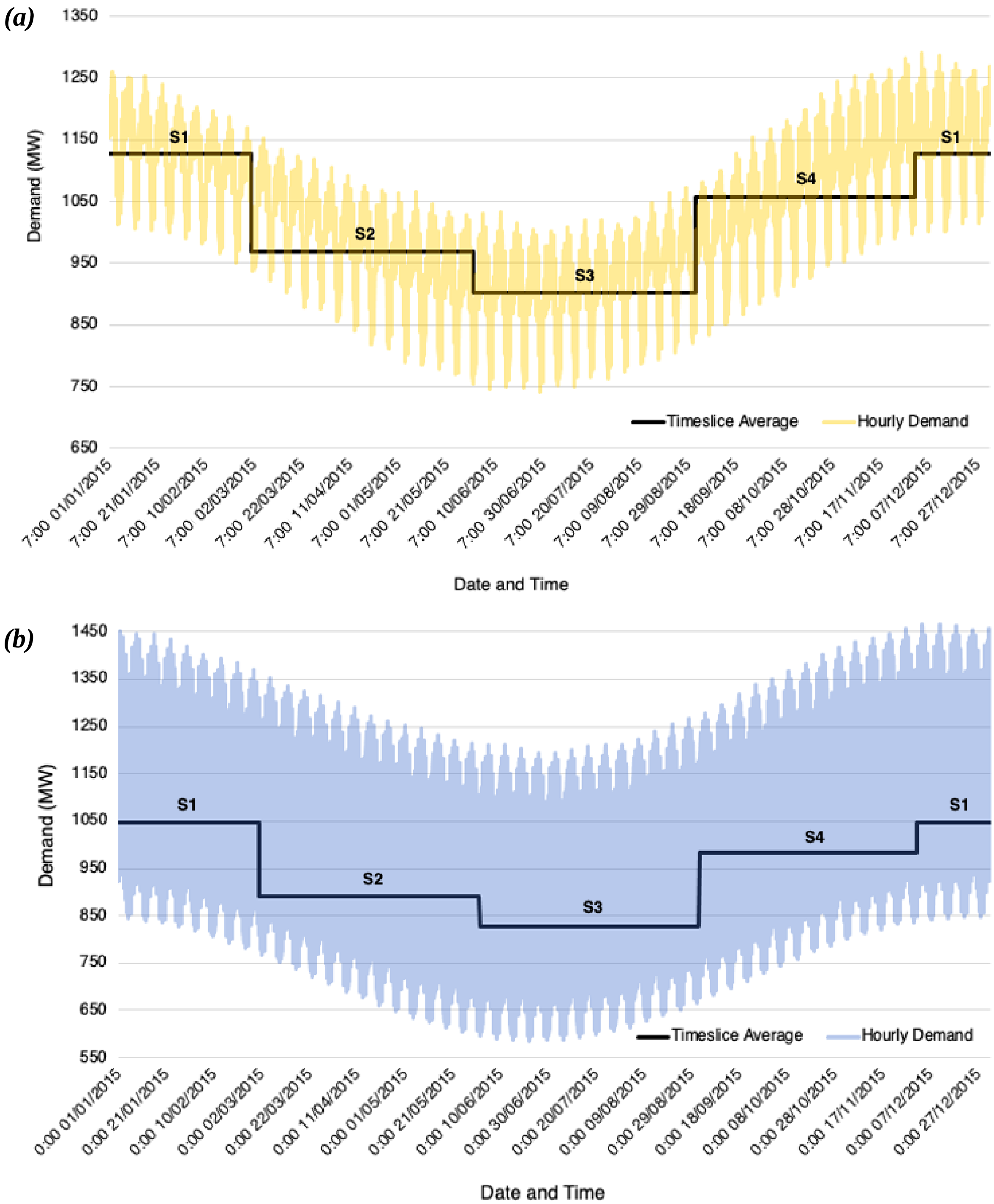

Figure 1. (a) 2015 hourly demand versus the timeslice average for D1 "day" hours and (b) D2 "night" hours for all four seasons in DRC, adapted from (Brinkerink and Deane, 2020)

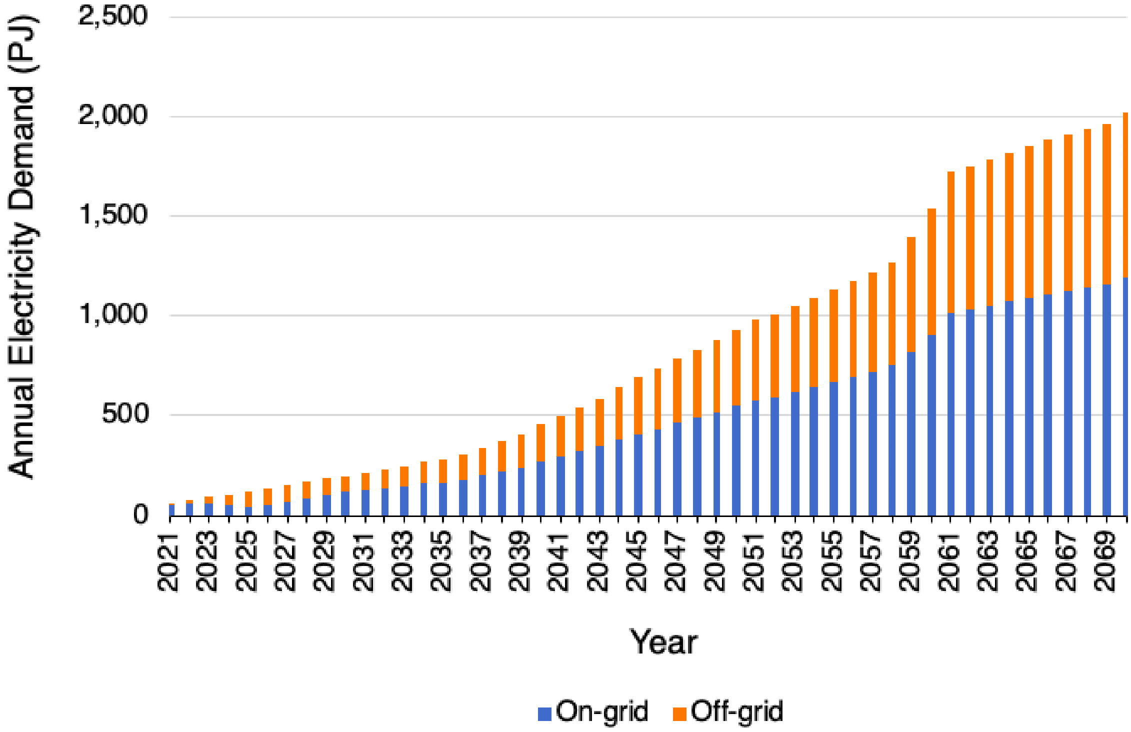

Figure 2. On- and off-grid generation ratio used to meet annual demand for all years, adapted from (Global Electrification Platform, 2020)

1.2 Supplying Off-grid Generation

Five different off-grid technology types are defined for this study: one oil-based diesel generator, and four RETs (Table 1). Because of DRC's large hydro potential, off-grid hydropower was included. Other studies promote the use of mini-grids and solar home systems (SHS) as off-grid solutions in the Congo River Basin or in developing African countries with low electrification rates like the DRC (Oyewo, et al., 2018; Bertheau et al., 2017), so these technologies are also modeled.

Table 1. Off-grid technologies included in model scenarios

Off-grid Technology Descriptions
Off-grid Diesel Generator (Decentralized) (1kW)
Solar PV (Distributed) with 2-hour storage (mini-grid)
Medium Solar PV (Decentralized) with 2-hour storage (1kW off-grid solar home system)
Small Solar PV (Decentralized) with 2-hour storage (0.3kW off-grid solar home system)
Off-grid Hydropower

Collectively, activity from these five technologies must fulfill (but cannot exceed) the annual off-grid demand for all years as defined above, subject to additional scenario-specific constraints. Achieving this using OSeMOSYS required grouping these five technologies and introducing constraints to force the production activity of this off-grid technologies group to exactly meet off-grid demand for all years (Table A).

1.3 Residual Capacity

For some technologies, known currently installed capacities needed to be accounted for in the model. These capacities installed before the beginning of the model period are known as residual capacities. All residual capacities are in

Table A.

1.4 Capacity Factors

For all solar PV and wind technologies included in the model, capacity factors were updated based on hourly solar and wind generation potential for 2019 from Renewables Ninja for Kinshasa, DRC (-4.3217, 15.3126) (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016). Capacity factors for hydropower technologies are based on 15-year averages from the PLEXOS-World dataset (Pappis et al., 2021). Hourly capacity factors were consolidated into the eight timeslices defined previously. All capacity factors are in Table A.

1.5 Financial

A discount rate of 10% is used across all model scenarios since this is in-line with the public cost of capital for renewable projects in DRC (Agutu et al., 2022). All cost inputs are in 2021 USD, and all foundational technoeconomic parameter model inputs are in Table A.

1.6 Power System Flexibility

Deep analysis of system flexibility is out of scope for this study. However, constraints on the maximum annual activity constraints were placed on all non-fossil fuel technologies in all scenarios to ensure that the DRC power system can still operate successfully even at very high proportions of renewable generation (see Table 2). These specific flexibility assumptions are recommended by Cannone et al., (2021) in the starter data kit for energy system modeling in DRC.

Table 2. Maximum annual activity limit placed on renewable technologies for flexibility (Cannone et al., 2021)

Technology Description	**Annual Activity Upper Limit** (% of total annual demand)
Solar PV Plant	15%
Solar PV with 2 hours storage	15%
Onshore Wind Plant	15%
Geothermal Plant	15%
Biomass Plant	30%

1.7 Projected Technology Capital Cost Reduction

For most electricity supply technologies, capital costs are projected to decrease each year based on additional research and development, changes in input prices, resource efficiency, and volumes of technology deployment (Rubin et al., 2015). In this study, rates of capital cost reduction were calculated using the National Renewable Energy Laboratory's Annual Technology Baseline (2022), which provides capital cost projections in terms of USD per kilowatt (kW) by technology up to 2050.

The year-over-year percentage decrease in technology cost was averaged from 2021-2030 and from 2030-2050. Capital costs beyond 2050 were held constant in the absence of additional data. Although capital costs for technologies varied across scenarios, these rates of decrease in cost were applied consistently. Further details on endogenously defined capital cost reductions rates are in Table A.

1.8 Constraints on Renewable Resource Potential and Annual Investment

Capacities can be constrained for the model period in OSeMOSYS using maximum capacity and/or maximum investment parameters. To reflect DRC's maximum hydropower capacity of 100-110 GW (World Bank, 2020), capacity was capped at 50 GW for both large hydropower (>100 MW) medium hydropower (10-100 MW) for all years. Geothermal was capped at 6.5 GW for all years (Makuku, 2019). Renewable technologies were also constrained in terms of annual capacity investment permitted in the model for all years (Table 3). Justifications for these limits explain how they prevent the model from producing unrealistic results. Table A summarizes how these constraints were applied using OSeMOSYS parameters.

Table 3. Maximum capacity investments included in the model by renewable technology type. Justifications from (IEA, 2021a; IEA, 2021b; IEA, 2021c)

Technology Type	**Annual Max Capacity Constraint** (GW)	**Justification**
Hydro	5	20% of annual global hydro additions in 2020
Wind	5	~$10B annual investment limit for the cheapest technology
On-grid solar	5	
Off-grid solar	2.5	~$5B annual investment limit for the cheapest solar technology

1.9 Emissions comparison to Nationally Determined Contribution

DRCs current NDC is a 2030 target of 21% reduction. Therefore, in this study, emissions across scenarios are evaluated against a hypothetical emissions reduction rate of 21% from 2021-2030 that is held constant past 2030 for the remainder of the model period, assuming DRC will commit to post-2030 emissions reduction NDCs or targets that are at least as ambitious as the present one.

2. MODELED SCENARIOS

To achieve the research objective and aims of this study, five scenarios were developed and run in OSeMOSYS based on introducing market-based (financial incentive) policies and various additional constraints. Table 4 summarizes the scenarios in brief. The model scenarios do not predict the future, nor are they forecasts, but the policy pathways they portray show the level of intervention that is necessary to achieve substantive differences in the profile of the DRC energy system.

Table 4. The five scenarios modeled in this study, their short names, and a brief overview of their most important features

Full Scenario Name	Scenario Short Name	Scenario Overview
Unconstrained	UNC	No additional model constraints added
Business as Usual	BAU	No investment in off-grid renewables permitted
Renewable Friendly	RF	16% capital cost reduction (subsidy) applied to all RETs
Fossil Hostile	FH	70% capital cost increase (tax) applied to all fossil fuel technologies
Renewable Friendly and Fossil Hostile (combined)	RF+FH	Both 16% RET subsidy and 70% fossil fuel technology tax applied

The RF, FH, and RF+FH scenarios are collectively referred to as the policy pathways in this study, since they are the three scenarios which result from policy intervention(s).

2.1 Scenario 1: Unconstrained

No additional constraints other than those described in the previous sections were used (i.e., the model is unrestricted in selecting the mix of off-grid technologies described in Table 1 to meet off-grid demand for all years). An unconstrained scenario is useful for comparison to the other scenarios because on- and off-grid demand can be met with the least cost technologies in an environment where no new policies have been introduced.

2.2 Scenario 2: Business as Usual

This scenario is intended to best mirror the current energy production development trajectory for DRC into the future. Importantly, it does not introduce constraints to maintain the current generation technology mix into the future, but rather maintains the current policy environment.

Additional minimum investment constraints were applied by totaling the capacities for 343 utility-scale energy projects planned in the DRC from 2022-2030 (Table 5). The maximum capacity for oil extraction is set to zero for all years because 100% of all DRC petroleum consumption for energy use comes from imported sources (International Trade Administration, 2021). Subsequent scenarios (RF, FH, and RF+FH) also include these minimum investment constraints and prevent oil extraction. In this scenario, it is assumed that no investment is made in off-grid renewable technologies. To achieve this, the activity limits placed on the grouped off-grid technologies were removed and instead placed on the diesel generator technology, forcing all off-grid generation to be realized by this technology (Table A).

Table 5. Government planned renewable energy projects through 2030 (ANSER, 2020). See source for further detail on individual planned projects

Technology Description	**Total Annual Minimum Capacity** (GW)		
	2022	**2025**	**2030**
Geothermal Plant	0.004	0	0.005
Medium Hydropower Plant	0	0.375	0.475
Small Hydropower Plant	0.088	0.266	0.119
Solar PV with 2 hours storage	0.061	0.159	0.208

2.3 Scenario 3: Renewable Friendly

Capital costs for all RETs (concentrated solar power, geothermal, hydro, solar, and wind) were reduced by 16% from 2022, simulating the introduction of VAT/customs import duty exemptions. Note, in this study, biomass is not considered a RET, since electricity generation using biomass emits greenhouse gases. The rates of capital cost reduction defined in Table A are maintained.

2.4 Scenario 4: Fossil Hostile

Capital costs for all non-RETs (biomass, coal, oil, and natural gas) were increased by 70% in 2022, simulating the introduction of a tax on energy generation from these technologies. Sensitivity testing model runs using incremental +10% increases in capital costs from +20% to +70% found that the most pronounced change in model outputs was achieved with a 70% increase in 2022. The rates of capital cost reduction defined in Table A are not maintained, meaning the higher price in 2022 for these technologies is held constant for the entire modeling period.

2.5 Scenario 5: Renewable Friendly + Fossil Hostile

The final scenario combines the capital cost changes made in scenarios four and five.

3. APPENDICES

3.1 Nomenclature

Table A1. One-to-one mapping of all power generating technologies included in all modeled scenarios and their respective technology codes

Technology	OSeMOSYS Technology Code Used
Biomass Power Plant	PWRBIO001
Coal Power Plant	PWRCOA001
Geothermal Power Plant	PWRGEO
Light Fuel Oil Power Plant	PWROHC001
Oil Fired Gas Turbine (SCGT)	PWROHC002
Off-grid Diesel Generator (Decentralized) (1kW)	PWROHC003
Gas Power Plant (CCGT)	PWRNGS001
Gas Power Plant (SCGT)	PWRNGS002
Solar PV (Utility)	PWRSOL001
Solar PV (Utility) with 2-hour storage	PWRSOL001S
Solar PV (Distributed) with 2-hour storage (mini-grid)	PWRSOL002
Medium Solar PV (Decentralized) with 2-hour storage (1kW off-grid solar home system)	PWRSOL003
Small Solar PV (Decentralized) with 2-hour storage (0.3kW off-grid solar home system)	PWRSOL004
CSP without Storage	PWRCSP001
CSP with Storage	PWRCSP002
Large Hydropower Plant (Dam) (>100MW)	PWRHYD001
Medium Hydropower Plant (10-100MW)	PWRHYD002
Small Hydropower Plant (<10MW)	PWRHYD003
Off-grid Hydropower	PWRHYD004
Onshore Wind	PWRWND001

Table A2. Names, descriptions, and units of key OSeMOSYS parameters necessary for modeling (Howells et al., 2011; Moksnes et al., 2015)

OSeMOSYS Parameter	Description	Units
CapitalCost	The one-time cost of creating a technology (assumed as overnight cost, so not spread over more than one year)	$/kW
CapacityFactor	Ratio of actual energy output over maximum energy output applied to each timeslice	-
FixedCost	Recurring annual costs for operating and maintaining a technology	$/kW/year
OperationalLife	How long a technology can function after it is created	years
SpecifiedAnnualDemand	Aggregated total demand for the year	PJ/year
SpecifiedDemandProfile	The annual fraction of energy-service or fuel demand that is required in each time slice (will sum to 1 for all technologies)	
ReserveMargin	The reserve level of installed capacity for a particular year	GW
TotalAnnualMaxCapacityInvestment	Constraint to put an upper limit on investment in new capacity of a technology for a specified year	GW/year
TotalAnnualMinCapacityInvestment	Constraint to put a lower limit on investment in new capacity of a technology for a specified year	GW/year
TotalAnnualMaxCapacity	Constraint to put an upper limit on the sum of all technology capacity allowed for a specific year	GW/year
TotalAnnualMinCapacity	Constraint to put a lower limit on the sum of all technology capacity allowed for a specific year	GW/year
TotalTechnologyAnnualActivityUpperLimit	Constraint to put an upper limit on the amount of production activity for a technology in a specific year	PJ/year
TotalTechnologyAnnualActivityLowerLimit	Constraint to put a lower limit on the amount of production activity for a technology in a specific year	PJ/year
VariableCost	Cost per unit of activity for a technology	$/kW

3.2 Scenario Constraints

Table A3. Summary of constraints applied in specified model scenarios for all years

	Applied to all scenarios				**Applied to BAU, RF, FH, and RF+FH**
	TotalAnnualMaxCapacity (GW)	**TotalAnnualMaxCapacityInvestment** (GW)	**TotalTechnologyAnnualActivityUpperLimit** (GW)	**TotalAnnualMinimumCapacity** (GW)
Technology	-	-	-	-
Biomass Power Plant	-	-	30% of total annual demand for all years	-
Large Hydropower Plant	50	5	-	-
Medium Hydropower Plant	50	5	-	2022: 0 2025: 0.375 2030: 0.475
Small Hydropower Plant	15	5	-	2022: 0.088 2025: 0.266 2030: 0.119
Off-grid Hydropower	-	5	-	-
Geothermal Power Plant	6.5	-		2022: 0.004 2025: 0 2030: 0.005
Solar PV w/ 2-hours storage	-	-	15% of total annual demand for all years	2022: 0.061 2025: 0.159 2030: 0.208
Other On-grid Solar Power Plants	-	5		-
Off-grid Solar	-	2.5		-
Onshore Wind	-	5	15% of total annual demand for all years	-

Table A4. Constraints applied in all scenarios except BAU to the off-grid dummy grouping technology in order to force the model to exactly meet but not exceed or fall short of the aggregated off-grid demand for all years. For the BAU scenario, these constraints on the dummy grouping technology were removed and instead applied directly to the Off-grid Diesel Generator technology to force it to meet all aggregated off-grid demand for all years

<table>
<tr><th>Technology</th><th>Dummy Grouping Technology</th><th>TotalTechnologyAnnualActivityLowerLimit (GW)</th><th>TotalTechnologyAnnualActivityUpperLimit (GW)</th></tr>
<tr><td>Off-grid Diesel Generator (Decentralized) (1kW)</td><td rowspan="5">“Off-grid technologies”</td><td rowspan="5">Total Off-grid Demand minus 0.01</td><td rowspan="5">Total Off-grid Demand plus 0.01</td></tr>
<tr><td>Solar PV (Distributed) with 2-hour storage (mini-grid)</td></tr>
<tr><td>Medium Solar PV (Decentralized) with 2-hour storage (1kW off-grid solar home system (SHS))</td></tr>
<tr><td>Small Solar PV (Decentralized) with 2-hour storage (0.3kW off-grid solar home system)</td></tr>
<tr><td>Off-grid Hydropower</td></tr>
</table>

Table A5. Residual capacities for technologies introduced in all scenarios from 2021 and then kept constant for all future years across all scenarios (Cannone et al., 2021)

Technology	**ResidualCapacity** (GW)
Oil Fired Gas Turbine (SCGT)	0.013
Gas Power Plant (SCGT)	0.025
Solar PV (Distributed) with 2-hour storage (mini-grid)	0.018895
Large Hydropower Plant (Dam) (>100MW)	2.533
Medium Hydropower Plant (10-100MW)	0.418
Off-grid Hydropower	0.1416
Power Transmission	1.18897
Power Distribution	1.12952

3.3 Technoeconomic Parameters

Table A6. Specific short-, medium-, and long-term capital cost reduction rates applied to generation technologies as model inputs for all scenarios unless stated otherwise (ANSER, 2020; Cannone et al., 2021; National Renewable Energy Laboratory, 2022)

Technology	**Annual Capital Cost Reduction Rate**		
	2022-2030	**2031-2050**	**2051-2070**
Biomass Power Plant	0.65%	0.65%	0%
Coal Power Plant	1.4%	1.4%	0%
Geothermal Power Plant	1.8%	0.05%	0%
Light Fuel Oil and Oil Fired SCGT Power Plants and Off-grid Diesel Generator	1.7%	1.7%	0%
SCGT and CCGT Gas Power Plants	0%	0%	0%
Solar PV (Utility)	4.7%	1.3%	0%
Solar PV (Utility) with 2-hour storage	6.3%	1.1%	0%
Solar PV (Distributed) with 2-hour storage (mini-grid)	4.6%	1.3%	0%
Medium Solar PV (Decentralized) with 2-hour storage (1kW off-grid solar home system)	9.4%	1.3%	0%
Small Solar PV (Decentralized) with 2-hour storage (0.3kW off-grid solar home system)	9.4%	1.3%	0%
CSP with and without storage	4.3%	0.1%	0%
Small, Medium, and Large Hydropower Plants	0.6%	0%	0%
Off-grid Hydropower	0%	0%	0%
Onshore Wind	3.0%	0.8%	0%

Table A7. Foundational technoeconomic data used as model inputs for the UNC scenario. NB: Other scenarios use updated costs as outlined in Section 2.3-2.5

Technology	OSeMOSYS Technology Code Used	On-grid or Off-grid	Capital Cost ($/kW in 2021) [1,2,3,4,5]	Fixed Cost ($/kW/yr in 2021) [1,2,4,6]	Operational Life (years) [1,2,4,6,7]	Efficiency [1,2,4,7]	Average Capacity Factor [1,2,4,8,9]
Biomass Power Plant	PWRBIO001	On-grid	2500	75	30	35%	0.5
Coal Power Plant	PWRCOA001	On-grid	2500	78	35	37%	0.85
Geothermal Power Plant	PWRGEO	On-grid	3500	120	25	80%	0.79
Light Fuel Oil Power Plant	PWROHC001	On-grid	1200	35	25	35%	0.8
Oil Fired Gas Turbine (SCGT)	PWROHC002	On-grid	1450	45	25	35%	0.8
Off-grid Diesel Generator (Decentralized) (1kW)	PWROHC003	Off-grid	750	23	10	16%	0.3
Gas Power Plant (CCGT)	PWRNGS001	On-grid	1200	35	30	48%	0.85
Gas Power Plant (SCGT)	PWRNGS002	On-grid	700	20	25	30%	0.85
Solar PV (Utility)	PWRSOL001	On-grid	900	17.91	24	100%	S1D1: 0.250 S2D1: 0.308 S3D1: 0.350 S4D1: 0.263 S1D2: 0.044 S2D2: 0.042 S3D2: 0.046 S4D2: 0.041
Solar PV (Utility) with 2-hour storage	PWRSOL001S	On-grid	1360		24	100%	
Solar PV (Distributed) with 2-hour storage (mini-grid)	PWRSOL002	Off-grid	4139	86.4	24	100%	
Medium Solar PV (Decentralized) with 2-hour storage (1kW off-grid solar home system)	PWRSOL003	Off-grid	2700	16.5	20	100%	
Small Solar PV (Decentralized) with 2-hour storage (0.3kW off-grid solar home system)	PWRSOL004	Off-grid	1731	16.5	20	100%	
CSP without Storage	PWRCSP001	On-grid	3900	40.58	30	100%	0.45
CSP with Storage	PWRCSP002	On-grid	5572	57.97	30	100%	0.45
Large Hydropower Plant (Dam) (>100MW)	PWRHYD001	On-grid	3000	90	50	100%	0.34
Medium Hydropower Plant (10-100MW)	PWRHYD002	On-grid	2500	75	50	100%	0.34
Small Hydropower Plant (<10MW)	PWRHYD003	On-grid	3000	90	50	100%	0.34
Off-grid Hydropower	PWRHYD004	Off-grid	3000	90	50	100%	0.34
Onshore Wind	PWRWND001	On-grid	1429	59.56	25	100%	S1D1: 0.018 S2D1: 0.018 S3D1: 0.036 S4D1: 0.021 S1D2: 0.031 S2D2: 0.029 S3D2: 0.094 S4D2: 0.034

Table A7 Sources (see main reference list for full citations)

1: IRENA (2021) - Africa-specific data
2: IRENA (2018) - Africa-specific data
3: IRENA (2016) - Africa-specific data
4: IRENA (2015) - Africa-specific data
5: ANSER (2020) - DRC-specific estimates
6: Lazard (2021) - Global data
7: European Commission Joint Research Centre (2019) - Africa-specific data
8: Pfenninger and Staffell (2016) - DRC-specific averages calculated using hourly data
9: Staffell and Pfenninger (2016) - DRC-specific averages calculated using hourly data

3.4 Final Energy Demand

*Table A8. Breakdown of projected energy demand for DRC in petajoules used in this study. NB: Additional available estimated end-use electricity demands (denoted with *) were included to get accurate annual demand totals, however, analysis of these technologies was out of scope for this study because they are not part of the DRC power sector. See (Pappis et al., 2021) for demands for all years.*

Final Energy Demand (PJ)	**2021**	**2030**	**2040**	**2050**	**2060**	**2070**
Industrial	42.0700	62.8529	139.9481	267.2040	404.8351	553.5227
Residential	16.8842	32.6876	72.7820	138.9633	210.5402	287.8673
Commercial	4.6380	8.9790	19.9926	38.1720	57.8336	79.0747
*Residential Electric Stove	0.2900	8.5853	98.9638	304.7263	580.8630	715.5472
*Electric Motorcycle	9.3143	85.7553	123.2501	140.0570	140.0570	140.0570
*Electric Car	0	0	0	42.6659	149.3308	213.3297
TOTAL	63.5921	198.8601	454.9366	931.7885	1543.4596	2020.9131

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