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

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Abstract

Keeping global warming from evolving into irreversible climate disaster requires immediate and sustained decarbonization of global energy systems. Of urgent priority are the energy systems in low- and middle-income countries (LMICs) where billions of people are projected to gain energy access in the next several decades. Therefore, leapfrogging traditional fossil fuel-based electricity production in favor renewable energy technologies is a critical issue area for sustainability. In the Democratic Republic of the Congo, political and economic challenges mean $44B in external investment is required to achieve its 2030 emissions reduction targets. Additionally, RETs are often more expensive.

This study sought to generate, evaluate, and recommend possible national policies for the DRC government to implement to most effectively boost growth and investment in RETs. Financial incentives were identified as the policy type most practical for DRC. Modeling the resulting energy systems for policy pathways involving a 16% RET subsidy, a 70% fossil fuel tax, and both in combination relative to no-policy baseline scenarios, the scenarios including the tax had the lowest net costs and the highest proportion of RETs (above 90%). Additionally, despite current reliance on hydropower to fulfill 98% of its energy needs, hydropower plays a very minor role in all modeled scenarios. Finally, a post-modeling market potential assessment was performed on the technology that dominated off-grid supply across policy pathways: the 0.3 kW small solar home system (SHS). Based on learning rates for solar PV, demand for the small SHS system in DRC (>160 million units in total) was found to be sufficient to substantially reduce the unit cost as deployment scales.

Putting results into context, emissions reductions for the policy pathways were higher than a past study focused on distributed RETs in DRC, and system costs were 15% higher than estimated in other analysis. These results provide a novel contribution to the literature by demonstrating how financial incentive policies can influence RET uptake in DRC specifically. Ultimately, this study yielded four policy recommendations for the DRC government:

1. Pursue financial incentives to catalyze DRC's renewable energy supply

2. Tax fossil fuel energy production

3. Re-evaluate focus on hydropower

4. Promote DRC as a healthy market for solar home systems

Introduction

Compared to other world regions, energy demand in sub-Saharan Africa is expected to grow the fastest, with a population set to double by 2050 (IEA, 2021a). Satisfying this demand will require an unprecedented increase in energy production, especially as the global community makes progress toward achieving Sustainable Development Goal 7 (provide energy access for all) (United Nations Development Programme, 2021). If this expansion relies predominantly on fossil fuels, then by 2050, African energy systems will have an emissions intensity twice as high as those in the rest of the world (van der Zwaan et al., 2018). Therefore, a critical requirement for meeting the Paris Agreement is ensuring sub-Saharan African countries leapfrog traditional fossil fuel energy development to instead generate a large majority of their energy supply from renewable sources.

Achieving this leapfrogging involves intentional national energy planning strategies that prioritize renewable energy technologies (RETs) over fossil fuels. However, these strategies remain infeasible and unrealistic while RETs are more costly. Yet, governments can implement policies to overcome these cost disparities. A recent study showed that not only does the decarbonization of energy supply contribute most to overall emissions mitigation but it is also highly responsive to policy signals (Bertram et al., 2021). Many other studies model possible scenarios to achieve varying outcomes of RET penetration in the energy systems of LMICs and then subsequently make policy recommendations to inform energy planning, such as for Chile (Ferrada et al., 2022), Costa Rica (Godínez-Zamora et al., 2020), Egypt (Rady et al., 2018), Ethiopia (Pappis et al., 2021a), and Tanzania (Rocco et al., 2021). This study builds on past research by taking the less commonly used inverse approach of developing model scenarios

based on the implementation of novel policies and then analyzing the energy system outcomes. In this way, results from this study are intended to be practical for a LMIC government.

In 2020, an estimated 82 million people in the Democratic Republic of the Congo (DRC) did not have access to electricity, the most of any country in the world (IEA, 2022). Due to political, infrastructural, and economic fragility, centralized grid expansion efforts in DRC have not led to increased energy access and the current policy environment is not favorable for private energy investment (World Bank, 2020). DRC was selected as the country of focus for this study because it has a substantial immediate need for energy access and insufficient policies to attract the private investment required to enable this access.

The primary research question for this study is: what actions should the DRC government take to develop the most sustainable and cost-effective energy system as demand increases? Thus, the overall research objective that follows from this question is: generate, evaluate, and recommend possible national policies for the DRC government to implement to most effectively boost growth and investment in renewable energy generation over the next several decades.

BACKGROUND

The current generation profile for the DRC is 98% renewable energy, almost exclusively from hydropower (IEA, 2019) but the country generates less than five gigawatts (GW) of hydropower out of a potential of 100-110 GW (Oyewo et al., 2018). Thus, the future role of hydropower is carefully considered in the current study's scenario results. DRC has commited to a nationally determined contribution (NDC) of 21% emissions reduction by 2030, the attainment of which is largely conditional on external investment (MEDD, 2021).

In October 2021, DRC formally updated the ambition of its nationally determined contribution (NDC) to a 21% reduction in economy-wide emissions by 2030 relative to projected business as usual emissions (BAU) (430 Mt CO_2e). (DRC does not have a more specific NDC sub-target focused on emissions reduction or mitigation in the energy sector.) A 19% reduction is conditional on international funding—referred to as foreign direct investment (FDI)—representing more than $44B of the estimated $48.68B in funding required to meet the full NDC (MEDD, 2021). DRC is not atypical: twenty-six African countries have conditional NDCs that rely on external investment (Senshaw and Kim, 2018). Conditional funding has become a common characteristic of NDCs for LMICs.

Sources from both academic and grey literature indicate that DRC is not currently conducive to external investment in RETs because of a lack of energy policies impacting RETs explicitly (Kusakana, 2016; World Bank, 2020; UK Aid, 2019). The most recent energy policy was passed in 2014, which liberalized on-grid electricity generation and T&D, established the Electricity Regulation Authority (ARE) and the National Agency for Electrification and Energy Services in Rural and Peri-Urban Areas (ANSER), but did not address RET cost or investment (ARE, 2014). Making DRC a favorable country for business investment will substantially increase the chance of success for its NDC.

The DRC National Development Plan for 2019-2023 includes five major strategic pillars. Pillar IV, Territory Development, has major objectives for the electricity sector, including leveraging greater private participation to finance the sector and intensifying investments in RETs. The funding section of the plan highlights accelerating reforms to improve the business climate and implementing specific incentive measures offering tax and customs advantages by sector as two major strategies for attracting

the FDI needed (UNDP, 2021). The importance of these strategies is further highlighted by DRC's stated goals of 30% electrification by 2025 and 60% electrification by 2030 (ANSER, 2020). Therefore, a priority gap for the DRC government to address is understanding which policies could be introduced to improve the business environment for RET investment.

There are three types of RET-supporting policies: targets, regulatory, and fiscal incentives/public financing (REN21, 2021). RET fiscal incentive policies were selected as the focus for this study because targets would be politically and legally challenging for the DRC to implement and regulatory policies cannot be easily integrated into energy system modeling.

Currently, DRC has a standard value-added tax (VAT) rate of 16% that is applied to all goods and services bought or sold for use or consumption in-country (PwC, 2022). VAT exemptions are applied to specific types of goods. Notably, "equipment, material, and chemicals imported by mining and oil companies for prospecting, exploration, and research" are VAT-exempt, providing a financial incentive for fossil fuel-based energy production (International Trade Administration, 2021). DRC import duties add up to an additional 19% to the cost of RETs. In theory, RETs should be exempt from VAT and customs import duties in DRC, but this has not been properly codified. Thus, the exemption is applied inconsistently, and, in many cases not at all (USAID and Power Africa, 2019). For two scenarios in this study, a conservative 16% subsidy (cost reduction) was applied to the capital cost of RETs for simplicity, which the DRC government could achieve through uniform application of a VAT exemption, or, if necessary, through a partial reduction of customs import duties.

For two scenarios in this study, a 70% tax (cost increase) was applied to the capital cost of fossil fuel technologies. Fossil fuel subsidy reform dominates the literature on applying financial disincentives to fossil fuel energy production (Jakob et al., 2014; Skovgaard and van Asselt, 2019). But, unlike most other countries, DRC does not have post-tax subsidies on petroleum, coal, or natural gas that could be eliminated (International Monetary Fund, 2015), so these approaches are not applicable. However, as detailed in the previous section, one straightforward tactic the DRC government might employ to implement a fossil fuel tax would be to eliminate the current VAT-exemption in place for fossil fuel-based energy production. In financial terms, removing the VAT-exemption (fossil fuel subsidy) would be equivalent to introducing a 16% tax.

Methods

Various secondary datasets were used to source inputs and constraints to leverage Open Source Energy Modelling System (OSeMOSYS), which is a bottom-up, least cost energy systems optimization model that is useful for energy infrastructure planning (Howells et al., 2011). Figure 1 shows the Reference Energy System (RES) used in this study, detailing all the technologies used and how they relate to each other. Parameter data values used in modelling are available in the supplementary materials accompanying this paper, and for values not explicitly states, those from (Cannone et al., 2021) were used.

On- and off-grid, renewable and non-renewable energy technologies were defined in the model to emulate the DRC power sector. Attributes of each technology incorporated in the model include, capacity factors, cost data, and operational life. Additionally, as needed, constraints were applied to technologies to limit their capacity and/or activity for specified year(s) to capture resource potential limitations of DRC.

Five off-grid technologies were defined (Table 1) and constrained to limit off-grid generation to a forecasted percent of total generation by year (Global Electrification Platform, 2020). Collectively, activity from these five technologies must fulfill (but cannot exceed) the annual off-grid demand for the model period, 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 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

Table 2 provides an overview of the five scenarios modeled using OSeMOSYS. RF, FH, and RF+FH are collectively referred to as the policy pathways.

Table 2. 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

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.

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. 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.

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.

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.

Scenario 5: Renewable Friendly + Fossil Hostile

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

Market Potential Assessment

Based on modeling outputs, a market potential assessment was conducted on the off-grid technology that dominated all policy pathways. This analysis not only quantifies projected cost savings as capacity increases but also provides a tangible market potential forecast to spur business investment (Oluleye et al., 2021).

The factor can parametrize the learning rate (LR) of a technology in logarithmic terms, capturing the "progress ratio" for a technology, or how much the cost of a technology is reduced when its installed capacity doubles (McDonald and Schrattenholzer, 2001). The initial number of units and initial capital cost of the technology can then be represented as A_0 and UC_0, respectively, while the new cumulative number of units and new capital cost can be represented as A and UC. Therefore, for a given year, the new capital cost incorporating learning-by-doing is calculated as

$$UC = UC_0 \times \left(\frac{A}{A_0}\right)^{-\beta}$$ *(Eq. 1)*

(Oluleye et al., 2021).

Results And Analysis

Generation and Capacity Profile

Figure 2 provides a view of the annual electricity production results for all five scenarios, while Figure 3 provides a complementary snapshot of cumulative capacities by technology for each scenario. By 2065, production from RETs is 66.2% for UNC, 30.3% (BAU), 81.8% (RF), 90.1% (FH), and 91.4% (RF+FH).

Although DRC's planned hydropower projects are included in the BAU scenario and all subsequent scenarios, on-grid hydropower capacity remains well below the technical potential for the country. Like geothermal, generation from on-grid utility scale solar PV (both with and without two hours of storage) is present across all scenarios and contributes close to 50% of on-grid supply. Coal production after 2050 contributes to as much as one-third of production for the UNC, BAU, and RF scenarios. All production from coal ceases by 2056 in the FH and RF+FH scenarios, which is in-part replaced by production from combined-cycle gas turbine (CCGT) natural gas plants.

As expected from the constraints applied to BAU to prevent expansion of off-grid RETs, all off-grid demand is fulfilled by distributed diesel generators. Disregarding BAU, the four other scenarios have a consistent split of which technologies supply off-grid capacity. By 2065, these three RETs reach 42.3% or 50 GW of off-grid capacity for small SHS, 37.1% or 43.8 GW for medium SHS, and 20.6% or 24.3 GW for decentralized hydropower.

Total System Costs

Based on the calculations above, the updated total system costs inclusive of the policy impacts of each scenario are shown in Figure 4. Costs for the UNC and BAU scenarios remain the same, while the RF scenario cost increased from the subsidy, and the FH scenario cost decreased from the tax. The RF+FH scenario cost both increased from the subsidy and decreased from the tax, but since the revenue generated from the tax exceeded the cost of the subsidy, the net change for RF+FH was a cost reduction. Previously, before policy costs were included, the RF scenario was the cheapest overall, but with the updated system costs that account for the policy costs, the FH scenario becomes cheapest. The policy pathway scenarios remain cost competitive with each other when the total cost for the model period, including the government costs, is considered.

Emissions Profile

Plotting CO_2e emissions over the model period demonstrates differences in emissions over time based on the emissions associated with operational energy production technologies unique to each scenario (Figure 5). The BAU scenario has the highest annual emissions overall for the entire duration, likely largely due to the constraint on off-grid RETs. Around 2055, BAU emissions dip substantially, which is likely attributable to several fossil fuel plants built earlier in the modeling period meeting the ends of their operational lives at the same time. The emissions trajectories for the remaining scenarios stay constant until around 2050 and then begin to diverge. DRC's 2030 NDC has been projected into the future, and notably only the FH and RF+FH scenarios achieve this level of ambition. These results show that as electricity demand increases substantially in DRC in the coming decades, the power sector is likely to make a larger contribution to emissions than in the past, signifying the importance of more substantial emissions mitigation actions in other sectors.

Considering cumulative emissions for the period from 2021 through 2065, the RF+FH scenario has the lowest level of emissions, followed closely by the FH scenario. The RF and UNC scenarios have similar cumulative emissions, while emissions for BAU are greatest (46% higher than the RF+FH scenario).

Market Potential Assessment

In four out of five scenarios (including RF+FH, the scenario with the highest proportion of RETs), 50 GW of small SHS cumulative capacity is reached by the end of the model period, demonstrating a substantial contribution to off-grid generation. An off-grid technology was prioritized for this additional assessment since off-grid supply could make up more than 40% of total energy generation in DRC by 2030 (Global Electrification Platform, 2020). As a worked example, because the rated power of the small SHS is 0.3 kW, then for a specified year

$$Total\ number\ of\ units = \frac{Cumulative\ capacity\ by\ year}{Capacity\ provided\ by\ one\ unit}$$

(Eq. 2)

meaning the total cumulative capacity of the small SHS in each year in kW divided by their 0.3 kW size yields the values of *A* needed for Equation 1. Capital cost inputs in OSeMOSYS are represented in $/kW, so for a specified year

$$Unit\ cost = Capital\ cost\ for\ tech\ in\ year \times Capacity\ provided\ by\ one\ unit. (Eq.\ 3)$$

resulting in the initial per unit costs used for UC_0 in Equation 1. Using model cost inputs and capacity outputs from the RF+FH scenario and Equations 1, 2, and 3 yields the values in Table 3. There was no small SHS capacity added in the scenario in 2021, so the values for A_0 and UC_0 used in Equation 1 are based on the initial capacity added in 2026.

Table 3. Parameters for small SHS market potential calculation using a 23% LR and Equation 1.

Year	A_0 (millions of units)	A (millions of units)	UC_0 ($)	UC ($)
2021	0	0	519.30	519.30
2026	0	28.25	263.36	263.36
2031	28.25	33.20	263.36	247.81
2036	28.25	58.93	263.36	199.59
2041	28.25	100.60	263.36	163.14
2046	28.25	114.01	263.36	155.62
2051	28.25	150.73	263.36	140.07
2056	28.25	166.67	263.36	134.86
2061	28.25	166.67	263.36	134.86
2065	28.25	166.67	263.36	134.86

Figure 6 plots the relationship between unit cost and manufacturing volume at all three learning rates, and the resulting curves were fit with power function trendlines.

From an initial capital unit cost of $519.30 in 2021, the unit cost of the small SHS is projected to reduce considerably once 166 million units are deployed. For the high, mean, and low LRs, the minimized cost at that level of deployment is $51.82 (90% reduction), $134.86 (74% reduction), and $201.08 (61% reduction), respectively. For all three learning rates, by 2031 there is at least a 50% cost reduction when 33.2 million units are installed, which is roughly one-fifth of the total volume needed to support off-grid demand through 2065. At a 23% LR, in later years, the trajectory of cost reduction from projected demand converges toward the costs endogenously incorporated in the RF+FH scenario (Table 4).

Table 4. Comparison of capital unit costs for 0.3 kW SHS used as inputs for the RF+FH scenario and the demand-based capital unit costs for the same system from the market potential assessment using a 23% LR

Year	RF+FH Unit Cost ($)	Market Potential Assessment Unit Cost ($)
2026	263.36	263.36
2031	173.59	247.81
2036	162.60	199.59
2041	152.30	163.14
2046	142.66	155.62
2051	135.38	140.07

After the initial year of 2026, the unit costs from the market potential assessment are higher than those input in the model, but the difference between the two costs decreases over time. For the 47% LR, the market potential assessment unit costs are much lower than the model input unit costs. As a result, for LRs greater than 23%, annual capital unit cost reductions from projected demand are likely to be higher than those achieved by the RF+FH policies alone.

Overall, in the context of the RF+FH scenario and the policies that enable it, the market potential assessment suggests there is sufficient demand for small SHS in the DRC market to substantially reduce the unit cost as deployment scales.

Discussion

Seven key takeaways summarize the results from the model runs and succeeding market potential assessment. (1) In no scenario does on-grid hydropower come close to DRC's potential for this renewable energy resource. (2) Instead, solar PV approaches or hits its on-grid capacity limit in all scenarios. (3) Likewise, supply from off-grid SHS dwarfs decentralized hydro, with the 0.3 kW SHS contributing the most of all off-grid technologies in scenarios where off-grid RETs are permitted. (4) The generation mix in 2065 is highest for the RF+FH scenario at 91.4% and next highest for FH at 90.1%. (5) Only the FH and RF+FH scenarios have emissions profiles that ultimately meet DRC's projected future NDC. (6) Accounting for total discounted capital, fixed, and variable costs for the model period, RF is the cheapest scenario, however, FH becomes the most affordable scenario once the costs and benefits to the government of the policies implied by the scenarios are considered. (7) A market potential assessment on the 0.3 kW SHS shows that at only one-fifth of the total deployment in all policy pathways, more than 50% of the cost reduction from learning-by-doing is achieved.

Generation and Capacity Profile

In the current study, the RF, FH, and RF+FH scenarios all include policies that are favorable for decentralized RETs, and renewables made up 70%, 90%, and 91%, respectively of total energy production in 2065. Diverging from the current hydropower dominated energy mix in DRC, hydropower comprises only a small amount of total capacity in all scenarios modeled in this study. In fact, no scenarios included further investment in large hydropower beyond residual capacity. Despite DRC's large hydropower potential, and even under the hydropower capital cost reductions included in the RF and RF+FH scenarios, hydropower is not a least cost option for meeting demand. These results are consistent with analysis by Oyewo et al. (2018), who concluded that the power production intended for the continually delayed large hydropower Grand Inga project could instead be achieved through solar PV and other renewables. Results from this study suggest that having hydropower play more than a very minor role in future energy production for DRC will not be the cost-optimal solution.

Total System Costs

Across the five scenarios, the total discounted system costs exceed the Africa Energy Outlook (IEA, 2019) cost projection. The IEA's sustainable development in Africa scenario estimates $199.4B in total energy costs for DRC for the period from 2019-2040 (2019). Converting to 2021 dollars as used in this study, this amounts to a total cost of $215.1B. From 2021-2040, the cheapest scenarios in this study were RF and RF+FH, both costing approximately $247.4B, which is 15% more expensive while also including two fewer years. Since no other future cost projections for the DRC energy system were identified for comparison, this study provides a helpful contribution to the literature on the cost of a sustainable transition. The IEA cost provides a lower bound and this study's total system cost is an upper bound, but with more recent data, the current study's $247.4B output for 2021-2040 may provide a more up-to-date picture of costs.

Emissions Profile

A similar comparison to other research can be made for emissions. Relative to UNC, which includes no policy intervention, the cumulative emissions from the FH scenario are 5.19% lower. Modeling covering five LMICs by Abbas et al. (2022) found that every 1% increase in environmental taxes (including market-based financial instruments) resulted in a 0.22-0.91% reduction in CO_2e emissions. Based on this finding, the 70% tax on fossil fuel energy production in FH would be expected to reduce emissions 15.4-63.7%. Therefore, DRC's energy mix may not be as responsive to environmental tax interventions as other countries. A possible

explanation for this difference might be DRC's lower level of development relative to Brazil, Russia, India, China, and South Africa, the countries covered in the Abbas et al. (2022) study. Additionally, the total emissions impact of the proposed fossil fuel tax in this study would extend beyond the power sector, meaning emissions reductions from the FH scenario are likely underestimated. Another reason may be that DRC's emissions from energy production are already very low at 98% renewable, which is different from BRICS countries. A comparison to results from countries more like DRC would be more relevant, but this was not possible based on existing literature.

Market Potential Assessment

Profit margins for companies that manufacture SHS for distribution in developing countries are low. Viable business models must therefore rely on large sales volumes to generate sufficient revenues to make this product segment worthwhile. The results of the market potential assessment on a 0.3 kW sized SHS show that at volumes of more than 150 million units, which were present across all policy pathways, unit capital costs decrease as deployment rises at expected LRs for solar PV.

STUDY LIMITATIONS AND FUTURE RESEARCH

Many of the results in this study are particularly sensitive to cost inputs for both RETs and non-RETs, with capital cost making the largest difference, since this makes up more than 90% of total costs for all RETs. Where available, technoeconomic parameters specific to DRC were prioritized, followed by Africa-specific data, and as a last resort, global data. Energy and cost data specific to DRC and other sub-Saharan African countries is often out-of-date, and, when accessible, typically only as secondary datasets from non-peer reviewed sources.

TEMBA was the only data source identified that provided an annual energy demand projection for 2021-2070 specific to DRC. According to TEMBA, total annual industrial, commercial, and residential energy demand in DRC will increase more than 32 times over this time period (Pappis et al., 2021b). Future research is recommended to understand differences in the policy pathway effects used in this study under alternate demand projections.

A review of the research base for power systems planning in West African countries found that the majority of studies have been conducted by foreign scholars, organizations, and research agencies (Bissiri et al., 2020). This study contributes to that majority. A key benefit of the OSeMOSYS modeling method is its much lower complexity and learning time, which should make it easier for uptake by LMIC energy planners. However, OSeMOSYS-based literature in West African countries is scarce (Bissiri et al., 2020). It is hoped that the transparency of this study will spur engagement and discourse with the DRC entities who are best equipped to leverage it for positive change.

Conclusions And Recommendations

This study set out to answer the research question of which actions the DRC government can take to build a sustainable and cost-effective energy system. Specifically, this entails encouraging growth of and investment in a national energy system that uses a high mix of renewable energy. The results and analysis of the scenarios modeled in this study highlight two policy pathways as the most favorable for the DRC energy system: FH and RF+FH. Each has its advantages. FH had the lowest net costs for the results period, even considering the cost reduction from the subsidy for RF+FH. In terms of renewable mix and emissions, however, RF+FH performed better than FH. Out of the three policy scenarios, RF had the highest ratio of fossil fuel capacity, the poorest emissions profile (both cumulatively and over time),and it was the costliest. In summary, four policy recommendations addressed to the DRC government arose from this study, which satisfy the overall research objective.

Recommendation 1: Pursue financial incentives to catalyze DRC's renewable energy supply

Based on DRC's level of development and political administrative capabilities, financial incentives are the most sensible policy for increasing renewable energy capacity. Implement renewable energy financial incentives in the near-term to achieve compounding results in RET growth, FDI, and development.

Recommendation 2: Tax fossil fuel energy production

Because a fossil fuel tax was part of both of the two most favorable policy pathways, explore implementing this policy. In particular, a simple starting place could be eliminating the VAT exemption for fossil fuel production operations.

Recommendation 3: Re-evaluate focus on hydropower

Limited budgets require a careful allocation of funds. This study showed a marked lack of hydropower in the DRC energy mix across all scenarios, with a much greater focus on solar energy. Perform additional analysis to validate results from this study: the cheapest renewable solutions for the long-term may not involve large hydropower projects.

Recommendation 4: Promote DRC as a healthy market for solar home systems

The market potential assessment performed as part of this study shows that 0.3 kW SHS are deployed in the policy pathways at sufficient volumes to drive down unit capital costs. Use the results of this study in communications with external organizations to promote FDI in this RET, which looks to be essential for DRC's sustainable energy evolution.

Declarations

CRediT author statement

Gbemi Oluleye: Supervision, Writing – Review & Editing. Mark Howells: Supervision. Carla Cannone: Data curation, Resources. Pierre McWhannel: Software. Rudolf Yeganyan: Resources. Naomi Tan: Resources.

U4RIA compliance statement

This work follows the U4IA guidelines [Source], which provide a set of high-level goals related to conducting energy system analyses in countries. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios, and results (Ubuntu / Community). The authors ensure all data, source code, and results can be easily found accessed, downloaded, and viewed (retrievability), licensed for reused (reusability), and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process

(reconstructability), ensuring the transfer of data, assumptions, and results to other projects, analyses, and models (interoperability), and facilitating per-review through transparency (auditability).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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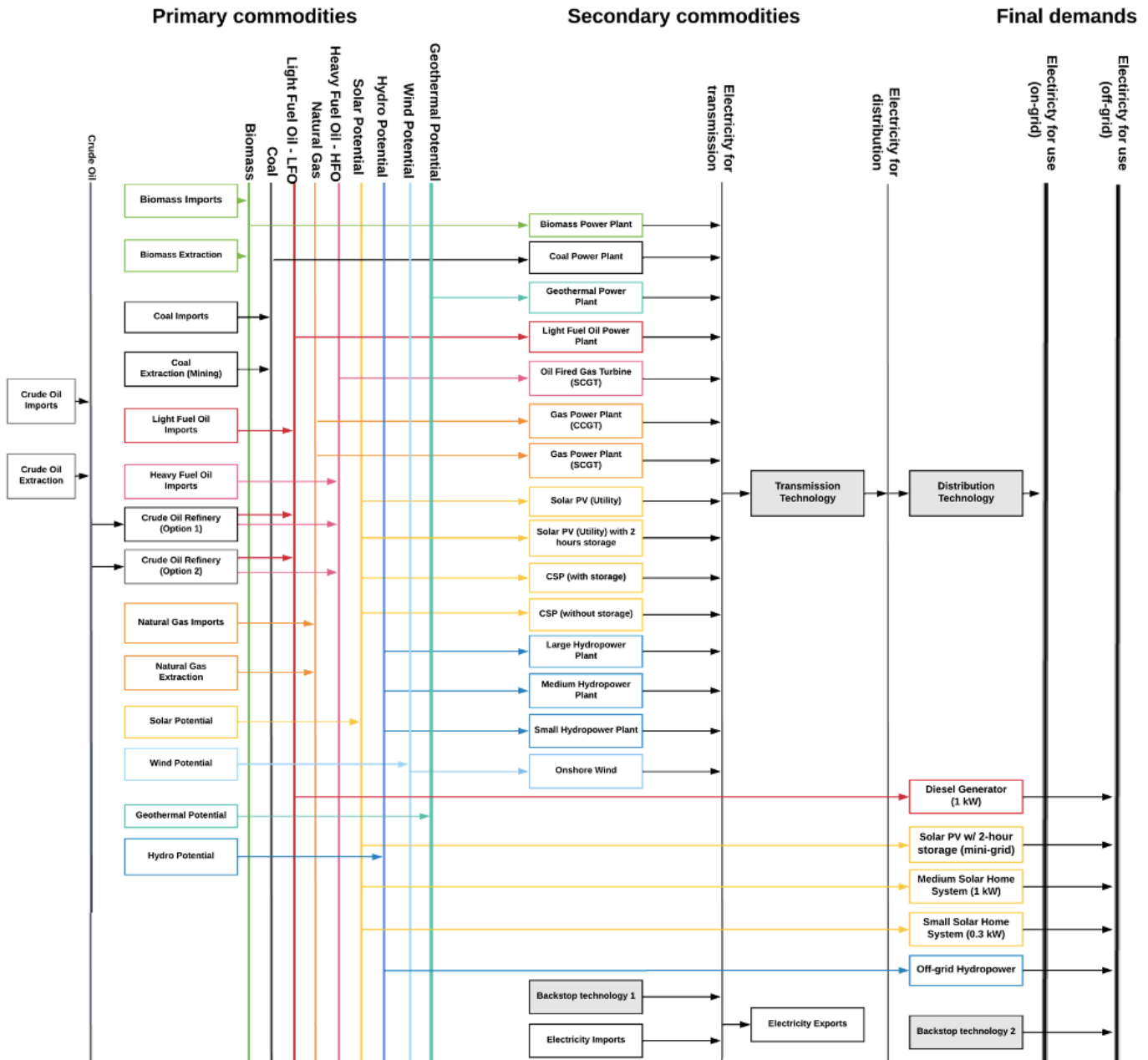
Figures

Figure 1

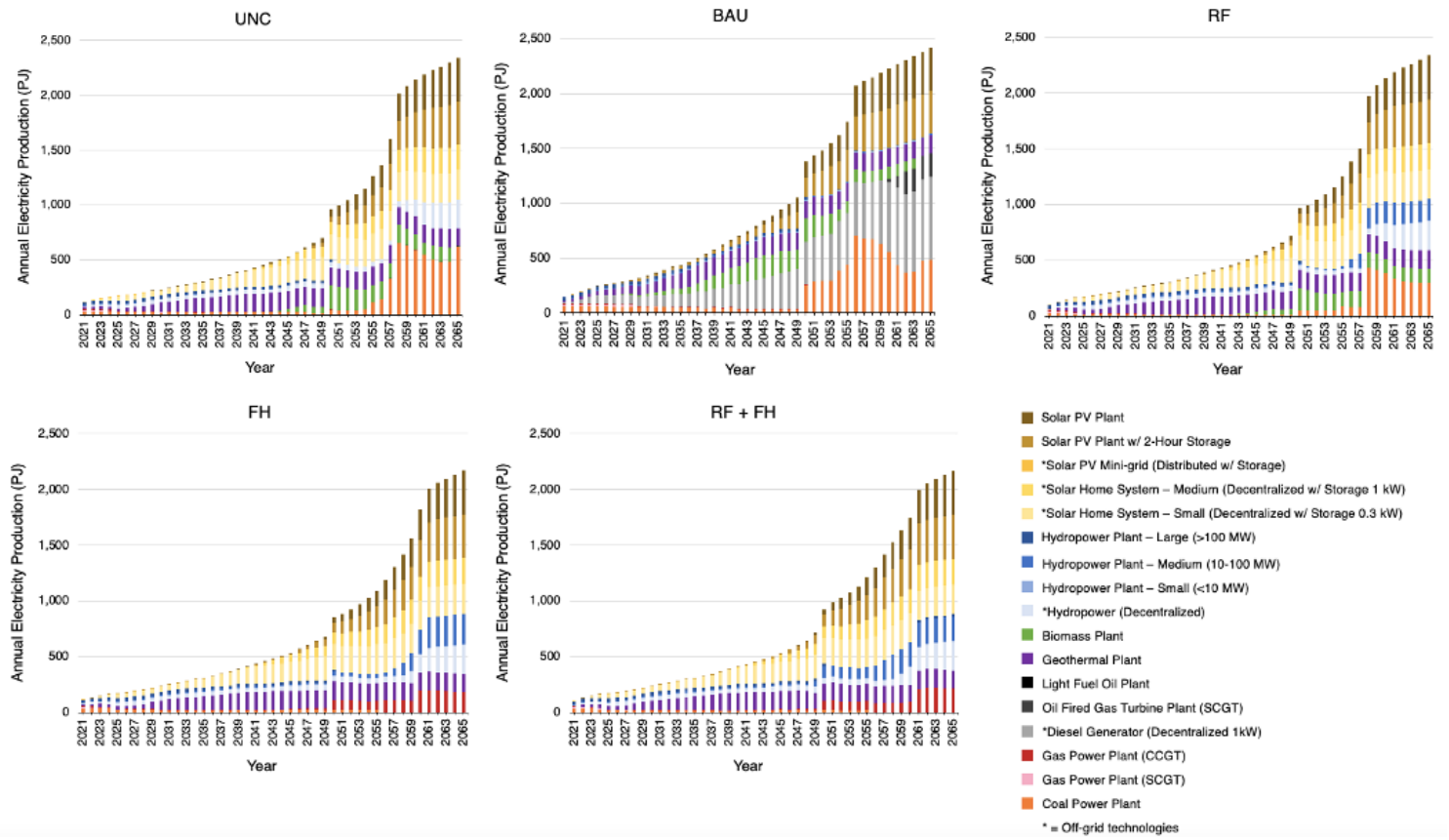Reference Energy System for the DRC power sector used in this study

Figure 2

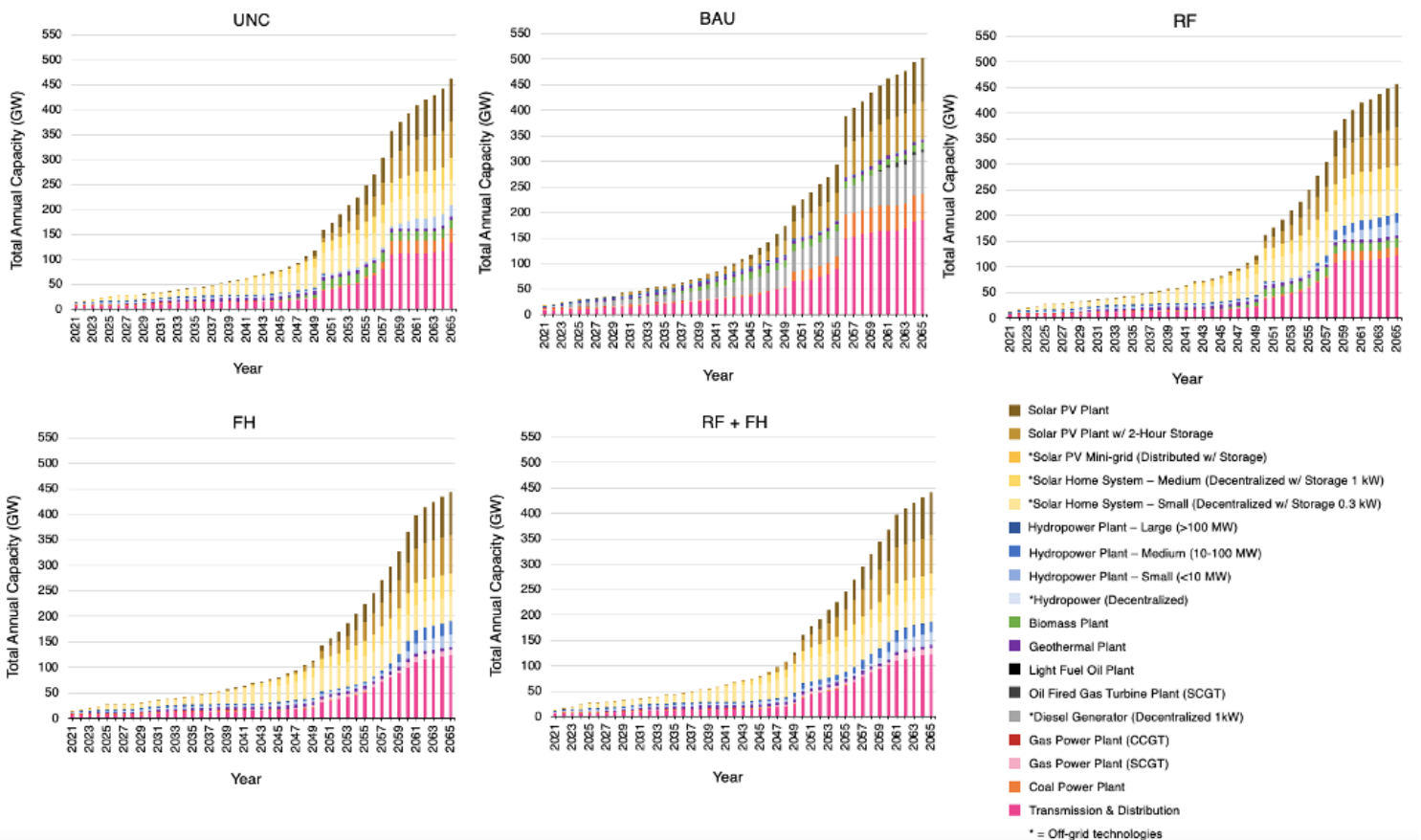Electricity production for the model period in petajoules across all scenarios

Figure 3

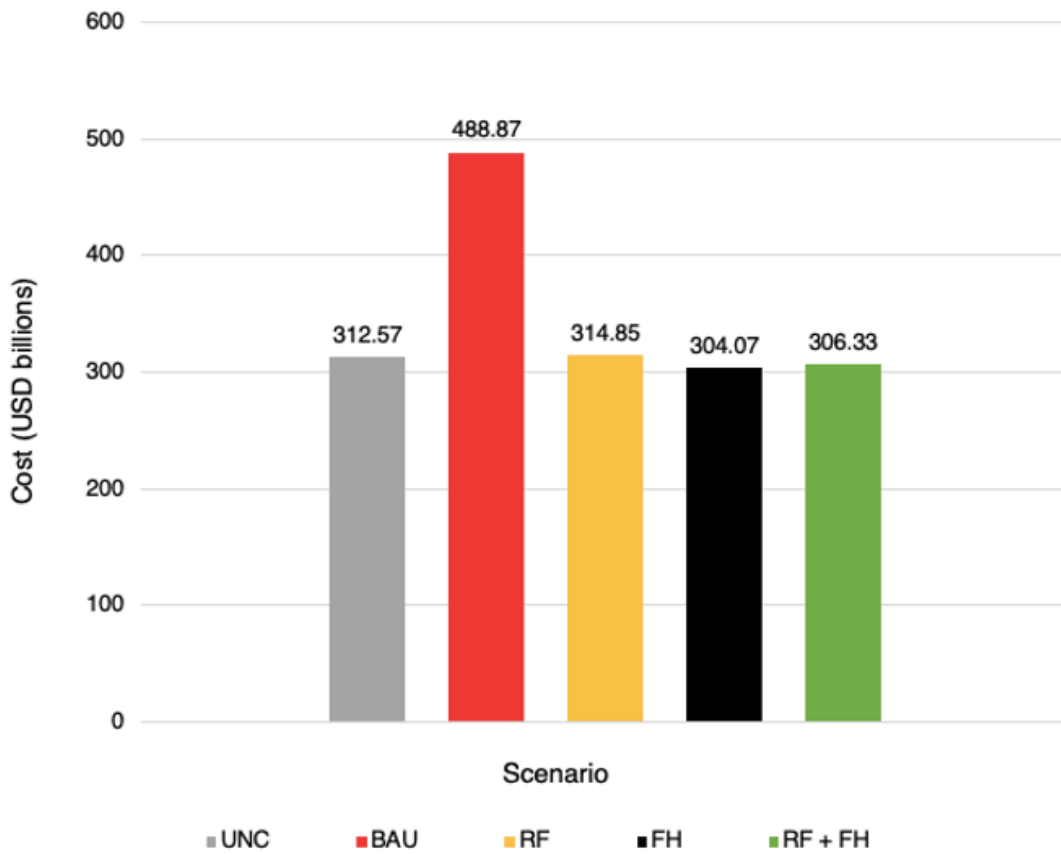*Annual capacity for the model period in gigawatts across all scenarios*

Figure 4

Total discounted costs of all scenarios, inclusive of policy costs (tax and subsidy) for relevant scenarios
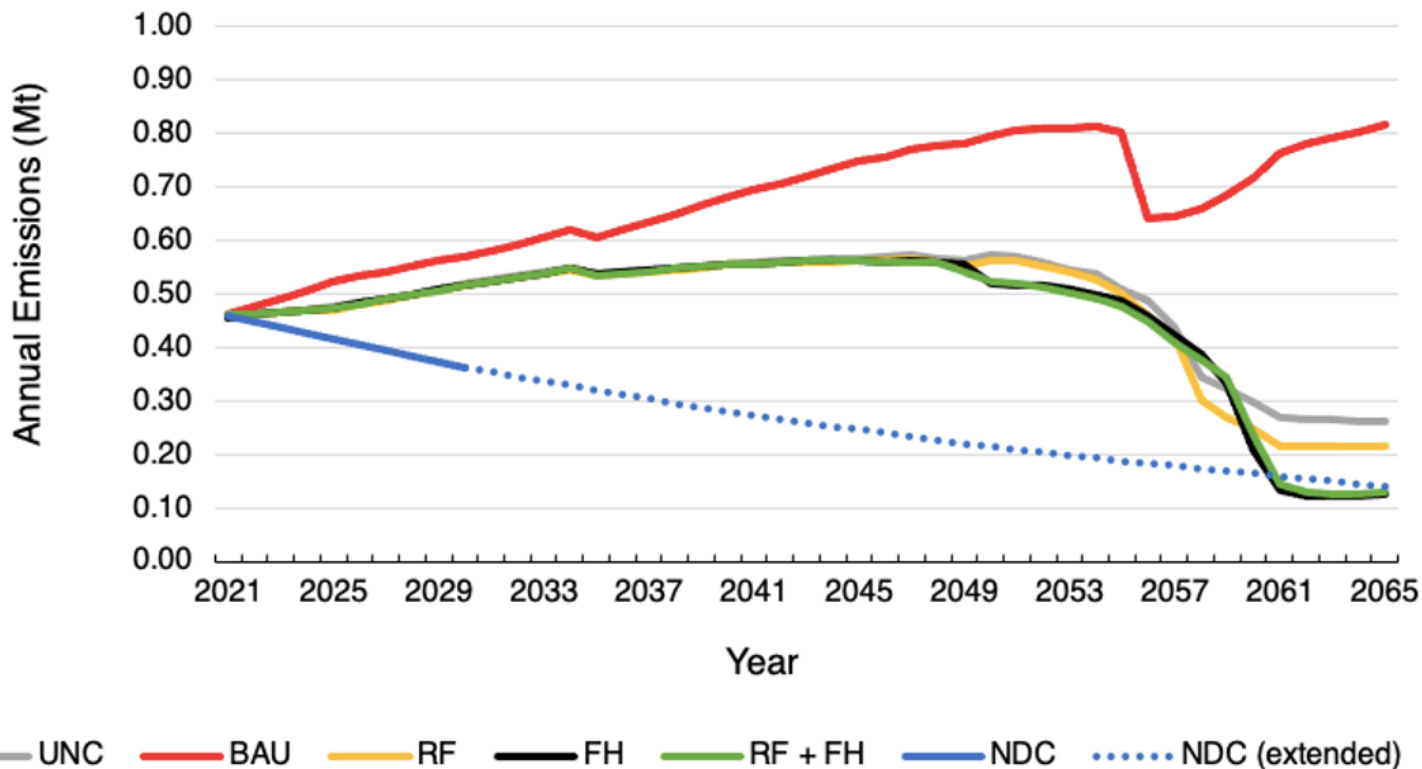
Figure 5

Model period CO_2e emissions plotted for all scenarios compared to the current 2030 NDC and future projected NDC for DRC
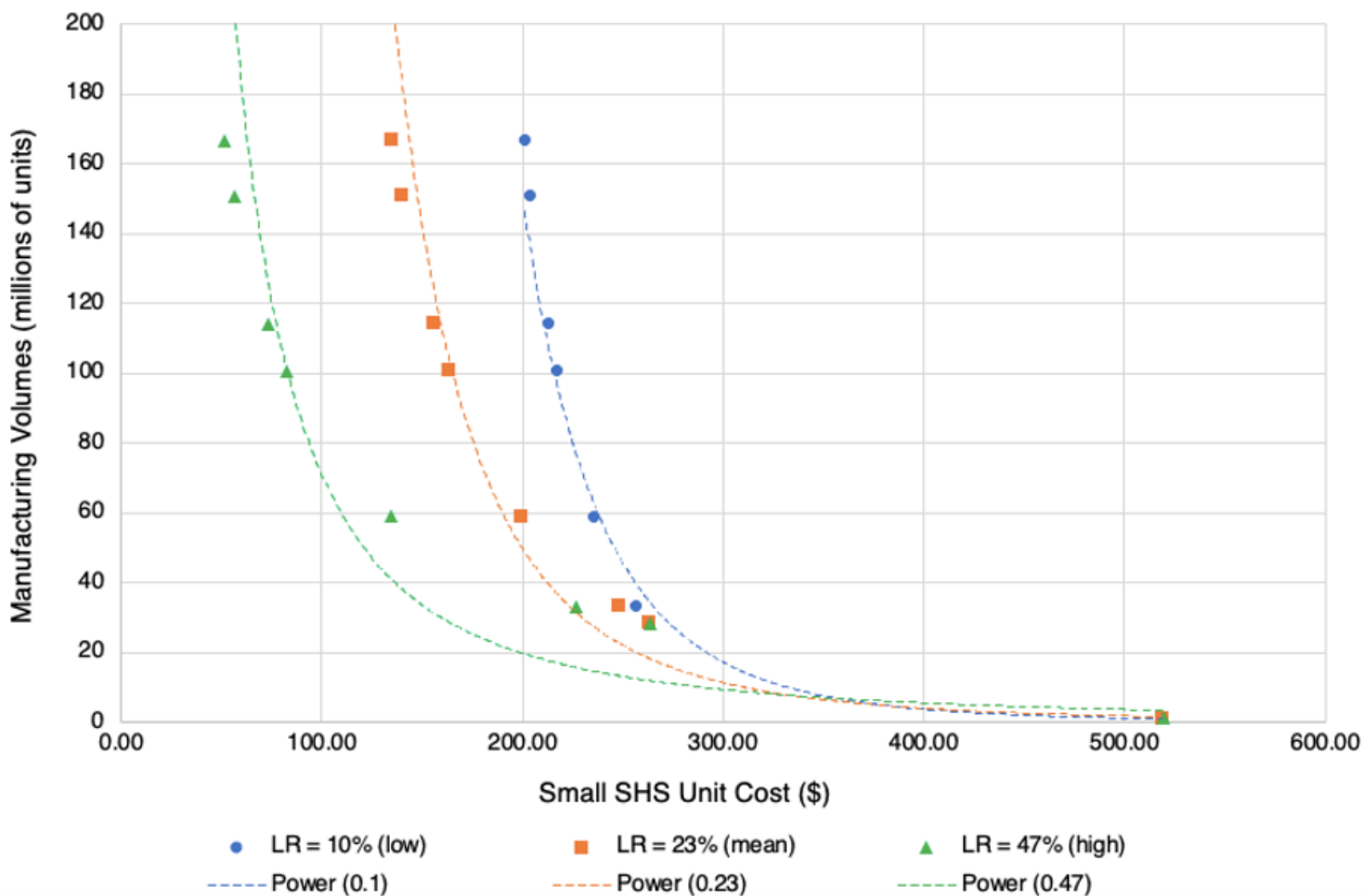
Figure 6

Additional post-model capital cost reduction for a 0.3 kW SHS driven by installed capacity at three possible learning rates for solar PV in the RF+FH scenario fit with power function trendlines

Supplementary Files

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- AppendixA.pdf