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Energy system development pathways for Ethiopia

Final project report

Synthesised findings of the PATHWAYS project

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Project Partners

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Executive summary

Ethiopia is a country endowed with an abundance of renewable energy resources, particularly in the form of hydro, wind, solar and geothermal energy. The country's power system – currently reliant on hydropower – needs to be developed to meet its growth ambitions, provide electrification to all consumers by 2025, and ensure long-term energy security. The complex and resource-intensive nature of energy systems, and their development, makes planning of critical importance. One of the ways in which planning and decision-making can be informed is through the use of energy system models to explore possible future pathways and their associated implications.

The PATHWAYS project sought to explore pathways for Ethiopia's electricity system to 2065 with the use of open-source energy system models, and to develop local capacity to use and build on those models for the country's energy planning and policy decision-support. The project adopted a participatory methodology that engaged local experts and stakeholders in the co-creation of knowledge, through multiple and mixed methods of inquiry typically adopted in fields of engineering and the social sciences. Some of these engagement activities included workshops and interviews that drew upon local expertise to shape the narratives and boundaries on the possible futures for Ethiopia's electricity system, as well as a household survey on energy consumer behaviour. In addition, we conducted four capacity development workshops; training students, academics, and staff of the government, not-for-profit and the private sector on the use of the Open-Source Energy System Modelling framework (OSeMOSYS). This project report highlights ways of building on the activities of the PATHWAYS project, and also answers three research questions:

i. What is the long-term future of Ethiopia's power sector, in meeting the country's growth ambitions and regional needs under Agenda 2065?
ii. What global lessons can Ethiopia learn to effectively govern the utilization of decentralised mini-grids in its electrification strategy?
iii. What strategic actions will enable effective household uptake of energy efficient technologies under the Ethiopian Energy Authority's Energy Efficiency Program?

We modelled electricity system pathways for four alternatives to the Business-as-usual (New Policies scenario), which were developed through outputs of a one-day workshop with local stakeholders consisting of representatives from the Ministry of Water, Irrigation and Energy (MoWIE), other key energy sector institutions, senior academics, multilaterals/bilaterals and the private sector. The High Ambition, Ambition, Big Business and Slow Down scenarios broadly represented futures in which the circumstances for the development of Ethiopia's power sector are either strong, weak, or inconsistent. Insights showed the need for a diversified mix of power generation sources for the country's grid electricity supply in the medium term, as the country's hydropower capacity is maximised in all but the most pessimistic of future demand growth. Solar PV and Concentrated Solar Power (CSP) technologies are set to play a major role in the future of the country's power system.

Our geospatial modelling of cost-optimal electrification patterns for Ethiopia provides further evidence that decentralised electricity systems have an important role to play in the country's plan to electrify all consumers by 2025. Under the government's National Electrification Plan (NEP 2.0), the role of decentralised systems will fall to 6% of the population by 2030, mostly serving demands in the southeast of the country. However, there are futures where it could be more cost-effective to keep some populations off-the-grid beyond 2030. In any case, there is a need to ensure a strong environment for the development and sustenance of a power system that is expected to transition between various degrees of decentralised and centralised connectivity over the short, medium, and possibly long term.

We reviewed the regulation and policy measures that have been successfully deployed in other countries for mini-grid deployment and found that Ethiopia has implemented many of these measures. However, despite these positive measures, our research shows there exist barriers to effective implementation of the established regulatory framework. Progress will require streamlined processes, stronger devolved institutions, and multi-stakeholder collaboration.

We surveyed 1400 urban households to identify the impacts of the government's electricity tariff reform on household behaviour and efficient technology adoption. Approximately 30% of respondents indicated that the higher electricity tariff had no impact on their energy behaviour, 50% became more mindful of combating wasteful electricity consumption, and 42% of all respondents decreased their use of the electric injera mitad and electric cookstove. Only 9% of respondents purchased efficient energy appliances as a response. Households indicated that two main barriers to the uptake of efficient appliances are the absence of product descriptions in local language and product prices. We explored the possible impacts of efficient technology on various scenarios of electricity demand growth in Ethiopia's residential sector using the Low Emissions Analysis Platform (LEAP). Our modelling suggests the potential of 30% in cumulative energy consumption savings by 2065 if Minimum Energy Performance Standards (MEPS) were fully implemented for household appliances by 2030. The implementation of efficient technology in the residential sector alone has the potential to reduce the required size of Ethiopia's power system capacity by 25GW by 2065 according to our analysis.

Outputs of the PATHWAYS project have been effectively disseminated both locally and internationally at academic conferences, and project workshops. The project's capacity development activities have equipped local researchers with the skills to train the next generation of Ethiopian energy system modellers. The government and its international partners can be encouraged to invest in building on the works of the PATHWAYS project, through further investment in inclusive skills development, and increased reliance on growing local expertise for energy policy decision-support.

Contents

1 Introduction

Background: Ethiopia context

Exploring future pathways is a process that is used by a range of institutions (government, private sector, utilities, academia) for long-term planning. It can be applied to issues of economic development, the climate, and other complex systems and processes that are critical to society and have uncertain futures, such as energy (BEIS, 2017; Deloitte, 2017; National Grid UK, 2017; IPCC, 2021; Shell, 2021). Energy systems are a key example of such complex structures as they tend to cover multiple interdependent sectors of the economy that require energy, from liquid fuels through to electricity. Focussing on the electricity sector, one important area of uncertainty that must be explored and planned for, is how various characteristics of the sector will evolve in the long term (e.g., 30-50 years). These characteristics – at a national level – include the demand for electricity, the resources and technologies used to produce electricity, the cost of producing, storing and transporting electricity, the formulation of the entire system (the extent to which it is centrally or otherwise administered), electricity trade (interconnection with neighbouring countries), and more. These uncertain issues are important considerations that must be thought about carefully for several reasons, including: the critical role of electricity as the backbone of any modern society, demand for electricity is continuously evolving, some of the energy resources used to produce electricity are either finite or inconsistent in their availability, in many cases the infrastructure used to produce and distribute electricity have long lead times and lifetimes, and the non-energy resources needed to make electricity available can be vast. This makes planning a critical area of government consideration, given their responsibility to ensure the various sectors of their economy are fit for purpose.

Ethiopia's National Electrification Program (NEP 2.0) sets out the government's detailed action plan to electrify the entire country by 2025, as the nation also reforms major areas of its power sector. In 2018, only 45% of the country's 109 million population had access to electricity, with the majority of those without access residing in rural areas (MOWIE, 2019). Under the NEP the government plans to provide 65% of its population with electricity via the national grid by 2025, and 35% via mini-grids and off-grid stand-alone systems, such as Solar Home Systems (SHS). Between 2025 and 2030, the government plans to increase the population receiving grid electricity to 96%, with the most remote populations (4%) continuing with service from systems off-the-grid (MOWIE, 2019).

In addition to these short and medium-term electrification plans is the need for long-term planning of the power sector to ensure critical goals such as energy security, can sustainably be met. Ethiopia's power sector is highly dependent on the country's vast hydropower resources, production from which is vulnerable to extreme variation in climate in the form of droughts. However, the country is also awash with non-hydro renewable resources including geothermal, biomass, wind, and solar resources. Ethiopia is also part of the East Africa Power Pool, with expectations that its hydro generation plans will have a major role to play in powering the region's growth under Africa's Agenda 2063 (AU, 2015), and its government has committed to limiting net greenhouse gas emissions in 2030 to 145 $MtCO_2e$ (or 64% below baseline projections) (FDRE, 2015). There is therefore a need to plan for, and regularly monitor, the country's long-term energy future, which rely on – amongst others – insights from modelled analyses of energy systems.

Project aims

In 2018, the Energy and Economic Growth Applied Research Programme (EEG) hosted a multi-stakeholder workshop to set research priorities for Ethiopia's energy and capacity development strategy (EEG, 2018). One of the key areas for research and capacity development identified was in "energy (and electricity) planning and modelling", upon which sound policies for sector development can be built. The Energy System Development Pathways for Ethiopia project (hereafter, PATHWAYS) responded to this need through a participatory research agenda that engaged local experts in the development of open access energy system models for the country, exploration of long-term pathways, and the enhancement of local capacity to build and use energy system models. In developing these models, a first set of future scenarios for the sector were explored. Furthermore, because this issue is an important responsibility of government and local scientific communities that inform government, it was necessary that these stakeholders were enabled to undertake future iterations of modelling exercises. Key among these were staff at Ethiopia's Ministry of Water, Irrigation and Energy (MoWIE). The aims of the project were as follows, to:

- enhance open-source energy system models for Ethiopia, and develop local capacity to use them
- explore Ethiopia's long-term power system pathways through participatory scenario development
- investigate consumer uptake of efficient technologies in the residential sector
- identify potential areas of governance and regulatory reform that could support sustainable development of Ethiopia's power system, with a particular focus on the role of decentralised renewables in the country's electrification plan

Structure of report
The rest of this report is structured as follows. Section 2 provides an overview of the overall methodology adopted for achieving the aims of the project; Section 3 answers three questions that encompass the outputs of the project; Section 4 discusses the present and anticipated future impacts of the project, before Section 5 concludes the report and highlights some areas for future work.

2 Participatory PATHWAYS Methodology

The PATHWAYS project adopted a participatory approach to its methodology that began with a stakeholder consultation process at the project kick-off meeting in Addis Ababa, December 2018, where representatives from government, utilities, local NGOs, academia, and civil society helped to shape the boundaries of useful activities and key focus areas. Multiple methods made up the integrated methodology (Figure 1) and involved the creation of data through primary field research and modelling tools. Detailed descriptions of the methods adopted and accessible links to tools can be found in specific reports published from this project (Ahmed *et al.*, 2021; Hassen, Seifemichael and Anandarajah, 2021; Tomei *et al.*, 2021; Usher *et al.*, 2021). Below is a brief overview of the project activities:

a) Field consultations and data collection for an up-to-date database of local energy resource, technology, power supply and demand, to develop and enhance two interlinked open-source models for Ethiopia at early stages of development – a least cost energy system model (OSeMOSYS), and a geospatial model of cost-optimal electrification expansion (OnSSET) (see Section 3).
b) A stakeholder workshop for interactive development of narrative storylines describing possible future pathways of Ethiopia's electricity system.
c) Interviews with local experts to elicit best perception and expectations about the drivers of future electricity demand.
d) An exploration of the role of efficient technology in household electricity demand pathways, using the Low Emissions Analysis Platform (LEAP).
e) Conducting a household survey to examine consumer behaviour and adoption of efficient technology in a transitioning electricity system.
f) Use of the above insights and data to model scenario pathways of the electricity system in the least cost optimisation and geospatial models respectively.
g) Undertaking modelling training workshops for students and local researchers across government, academia, not-for-profit, and the private sector, led by overseas and locally-based project researchers, using the models developed by the project.
h) Power sector policy and governance recommendations, making use of scenario modelling insights.

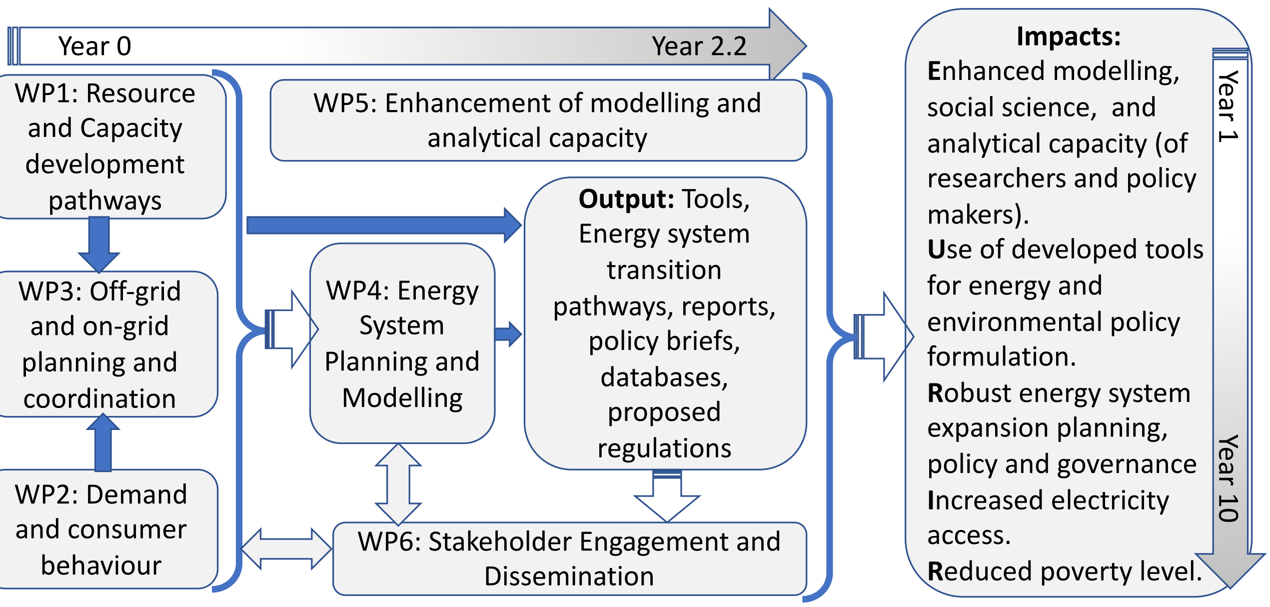

Figure 1: PATHWAYS integrated methodology

Box I : A note on COVID-19

The onset of the coronavirus pandemic required changes to planned project activities in 2020 due to local stay-at-home lockdown measures, restrictions to international travel, and cuts to project funding. Fortunately, much of the core project field work and activities had been undertaken in 2019, limiting the adaptation steps required. Nevertheless, these challenges affected some portions of fieldwork, including the planned household survey, and several stakeholder engagement and dissemination activities scheduled for the closing stages of the project. To ensure these affected activities went ahead, the survey methodology was adapted for the purpose of a telephone survey, and stakeholder engagement and dissemination activities were suitably organised and executed online. The latter was particularly enabled by the strong networks of local project partners, and the establishment of project awareness among stakeholders at the start of the project. Early efficiency of project activities enabled the project to still meet desired outcomes despite challenges caused by the pandemic. For example, the development of local expertise within locally-based project partners over the course of the project, enabled post-2020 stakeholder training activities to be led by local partners as opposed to externally-based project partners (as was the case in the earlier stages of the project).

3 Ethiopia Electricity System Pathways

Modelled scenarios of the future of Ethiopia's power sector were a central feature of this project. The country's power system is expected to take on a dual nature, with the extensive use of decentralised mini-grids in addition to significant expansion of its centralized power infrastructure, which pose important governance considerations for long term stability. Our analyses enabled us to also explore the role of energy efficiency in the country's residential sector. Thus, in this section we answer the following three questions:

iv. What is the long-term future of Ethiopia's power sector, in meeting the country's growth ambitions and regional needs under Agenda 2065?[1]
v. What global lessons can Ethiopia learn to effectively govern the utilization of decentralised mini-grids in its electrification strategy?
vi. What strategic actions will enable effective household uptake of energy efficient technologies under the Ethiopian Energy Authority's Energy Efficiency Program?

Long-term future of Ethiopia's power sector

We investigated the long-term pathways of Ethiopia's power sector under five plausible scenarios, primarily using two soft-linked quantitative models: 1) the Open-Source Energy System Modelling framework (OSeMOSYS), which focusses on cost-optimal electricity supply; and 2) the Open-Source Spatial Electrification Tool (OnSSET), which – in this work – spatially considers the cost-optimal means of meeting latent residential electricity demand (grid vs. mini-grid vs. off-grid). Among a number of useful insights (see Usher et al. (2021)), the results highlight the critical importance of a diversified portfolio of power generation technologies in the period following the year 2030, as Ethiopia contributes to Africa's 2063 growth ambition.

Hydropower dominates Ethiopia's installed electricity generation capacity, and in 2019 it accounted for over 4.2GW. Generators using wind, diesel, biomass, geothermal, and solar energy bring the country's 2019 total installed capacity to just under 5GW (MOWIE, 2019). Under current plans to increase the installed generating capacity, hydropower is expected to maintain this dominant role in the power sector through to 2026, having an exploitable resource potential in the region of 45GW (MOWIE, 2019). The country's other power-generating resources remain largely unexploited, including those renewable, where less than 1 percent of its solar, wind and geothermal potentials are being exploited (Asress *et al.*, 2013).

[1] We modelled to the year 2065 to generate pathways and insights in view of Africa's Agenda 2063.

Table 1: Ethiopia's estimated energy reserves

Resource	Unit	Exploitable Reserve	Exploited Percent
Hydropower	GW	45	<20 percent
Solar	kWh per square-meter per day	5 – 6	<1 percent
Wind Power	GW	10	<1 percent
Geothermal	GW	5	<1 percent

Source: Asress et al. (2013)

Five future pathways were developed through the participatory workshop held with stakeholders across Ethiopia's energy landscape in August 2019. The pathways consider issues of access to finance, economic development, technological availability, and energy policy continuity. In addition to a "New Policies" scenario – in which the power sector takes a path in line with current policies, such as those outlined in NEP – pathways capturing the possibility of slower economic growth and missed sector targets (e.g. Slow Down scenario), and those where goals are outperformed (e.g. High Ambition scenario) were also considered (see Usher et al. (2021)). An overview of differences in the scenarios and their modelled parameters can be found in Table 2.

Table 2: Overview of scenarios

	New Policies	Slow Down	Big Business	High Ambition	Ambition
Total electricity demand growth	High	Low	Very High	Very High	Very High
Residential demand tier shares (2030)					
Universal Access	2025	2042	2042	2025	2025
Max Connections (2030)	-	500,000	500,000	-	-
Max Connections (2050)	-	1,000,000	1,000,000	-	-
Proximity Constraint	<25km	<2km	<2km	<25km + exp.	No + exp.
Future committed investments (implementation year)	As per current policies	5 years delay on the current start year	As per current policies	As per current policies	As per current policies
Interconnector capacity available for export	No limit driver by electricity export price	No limit driver by electricity export price	No limit driver by electricity export price	100%	70%
Discount rate	10%	20%	8.5%	5%	8.5%
Technology availability	Section 4.1.1 (all technologies allowed)	Section 4.2.1 No nuclear	Section 4.3.1 (all technologies allowed)	Section 4.4.1 (all technologies allowed)	Section 4.5.1 (all technologies allowed)

Source: Usher et al. (2021)

Note: Tier levels are adapted from Bhatia and Angelou (2014) to the Ethiopian context, where tiers 1, 2, 3, 4, and 5 correspond to the colours in the table blue, sky blue, green, purple, and red respectively.

The only instance in which Ethiopia's hydropower potential is not fully exploited before 2065, is if the country does not realise its economic development ambitions and the demand for electricity across key sectors experiences minimal growth (Slow down scenario). In all other scenarios considered, Ethiopia's vast hydropower potential is fully exploited, in some cases as early as 2041 (Big Business), necessitating the reliance on intermittent renewables to meet future growth. Indeed, in multiple scenarios explored, demand growth is such that solar PV and concentrated solar power (CSP) technologies combine to become the dominant resource for electricity generation in the country by 2065, in terms of installed capacity (High Ambition and Big Business) Figure 2. This potential future dependence on intermittent renewables and continued demand growth increases the need for electricity generation from fossil fuels in the form of natural gas and fuel oil, along with the potential need to invest in nuclear power plants. The question of how to best manage carbon emissions from Ethiopia's power sector may well be relevant in its future system. Ethiopia can also be an important exporter of electricity to neighbouring countries, in the event of stable, high electricity export prices. Depending on export price, electricity system size, and future investment in interconnector capacity, we observe the potential for annual electricity exports between 20-40TWh, with the potential to raise between $48 billion and $280 billion (undiscounted) in cumulative revenue.

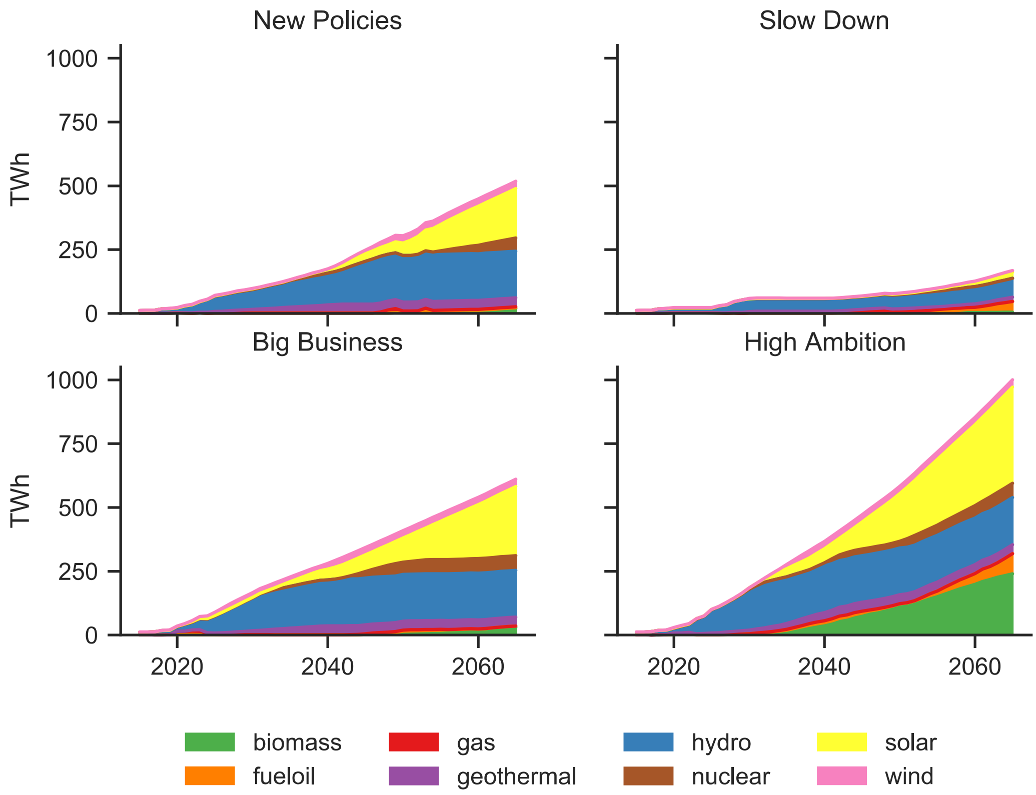

Figure 2: Electricity supply mix by technology (TWh) in key model years by scenario

One of the interesting findings of the electrification pathways we explored for Ethiopia are the potential cost savings that may be possible, depending on the policy choice of the government. The government's plan for 95% of the population to be served by the grid by 2030 under the NEP, is captured in the New Policies scenario explored by our geospatial electrification model. However, our analysis shows that absent the above NEP policy, the least-cost electrification pathway for a scenario where growth in household electricity demand is highest (Ambition scenario), there are many areas of the country that are more cost-effectively met by stand-alone PV technologies, due to the presence of limited household demand. This comparison in policies (i.e., grid connection target vs. least cost) can be seen between the 2030 electrification maps for the New Policies and Ambition scenarios in Figure 3. The potential cost savings were up to US$7 billion by 2030. However, it should be noted that our least cost electrification analyses only considered demand pathways for households. The inclusion of other sectoral demands in our geospatial analysis, might increase demand levels across the country, therefore varying the least cost technological profile, which may decrease the savings possible if such a policy was adopted.

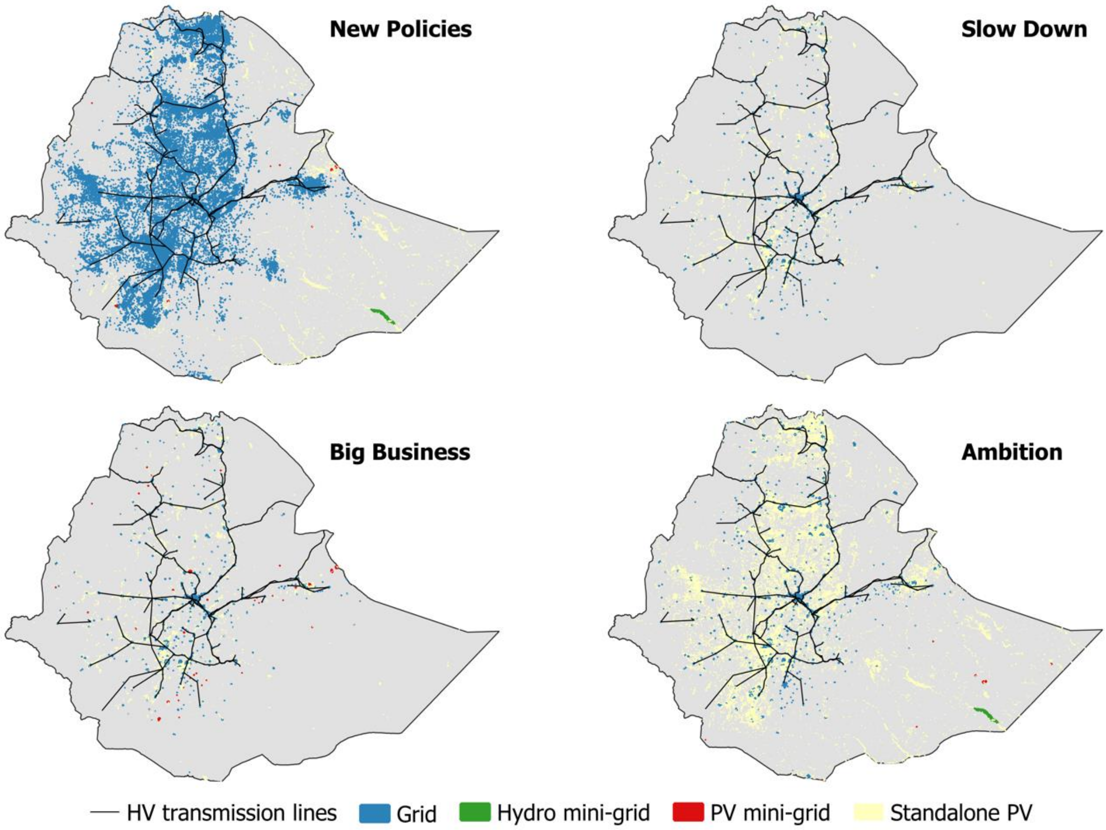

Figure 3: A comparison of four spatial patterns of residential electrification in 2030

Box II : Key findings on long-term future of Ethiopia's power sector

- Alternative technologies are required to meet long term demand for electricity after hydropower potential is fully utilised by medium term.
- Solar power becomes the dominant resource for electricity generation by 2065.
- Long-term reliance on intermittent renewables can necessitate increased supply from fossil fuels for energy security if storage, imports or other stable sources of power supply are unavailable.
- Significant revenue in the hundreds of billions of dollars are possible through electricity exports over the next 50 years.
- Possible cost savings of up to US$ 7 billion if electrification strategy adopts a least-cost policy.

Governing decentralised mini-grids in Ethiopia's power sector

The government of Ethiopia is implementing 12 hybrid/fully renewable mini-grid pilots, and expects 285 more to be built on the road to universal electrification by 2025 (MOWIE, 2019). Our scenarios show that hundreds more will be required through to 2070. This is the case in all scenarios to varying degrees, as regions in the southeast are more cost effectively served by mini-grids rather than the grid, even in the long term. In some scenarios, the grid extends over time to an area with previous mini-grid operation, such as with the Big Business scenario between 2050 and 2070 (Figure 4), where the previously isolated mini-grids are connected to form part of the central grid infrastructure. Given this long-term involvement of mini-grids in Ethiopia's power sector, there is an important question of how the complexities of a dual power system will be governed effectively.

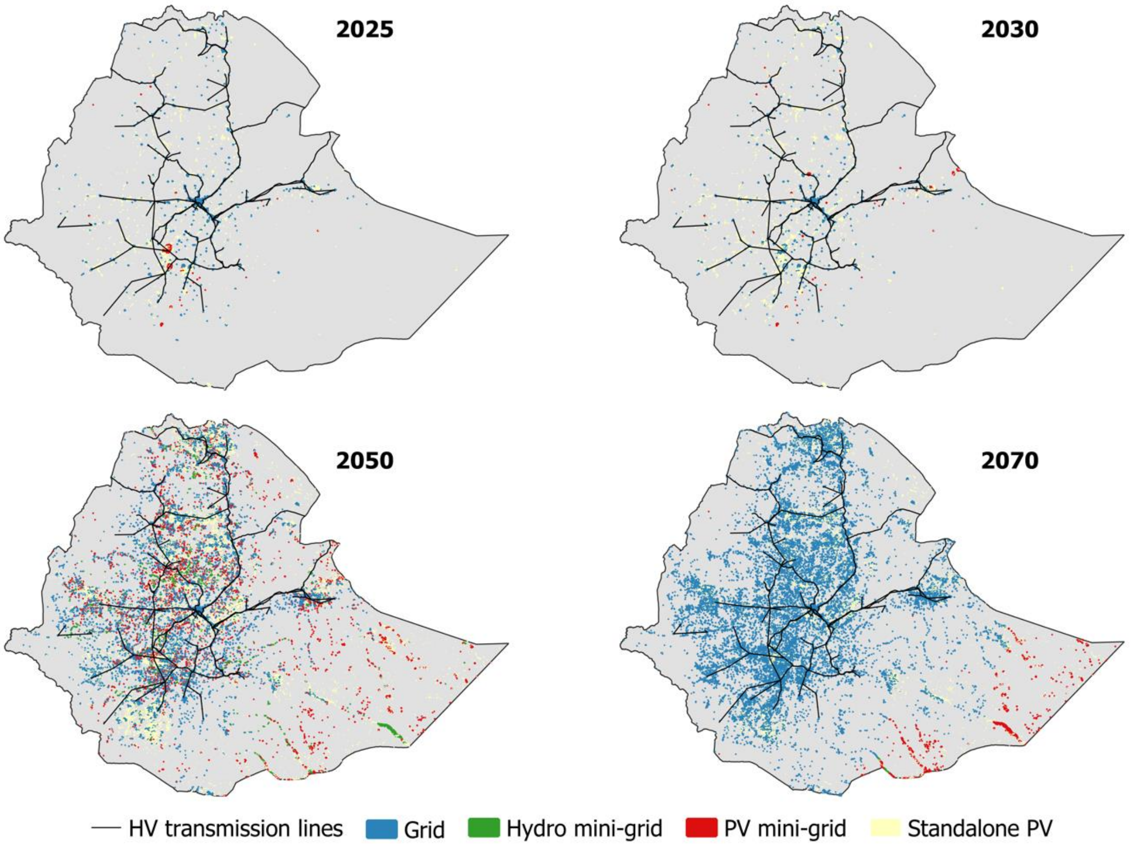

Figure 4: Big Business scenario

We undertook a review of Ethiopia's mini-grid provisions through document analysis to ascertain the existence of measures that shape a strong policy framework for mini-grid deployment, effective regulation of mini-grids, and other supporting measures for renewable mini-grid deployment, according to global best practice (see Figure 5). Following this, in June-July 2020, we collected primary data through semi-structured interviews with key stakeholders, to investigate practical experiences with any existing measures. We found that while Ethiopia's mini-grid policy and regulatory measures have developed to cover many globally recommended needs, the implementation and uptake of these measures has been slow. Our findings under this work are detailed in (Ahmed *et al.*, 2021).

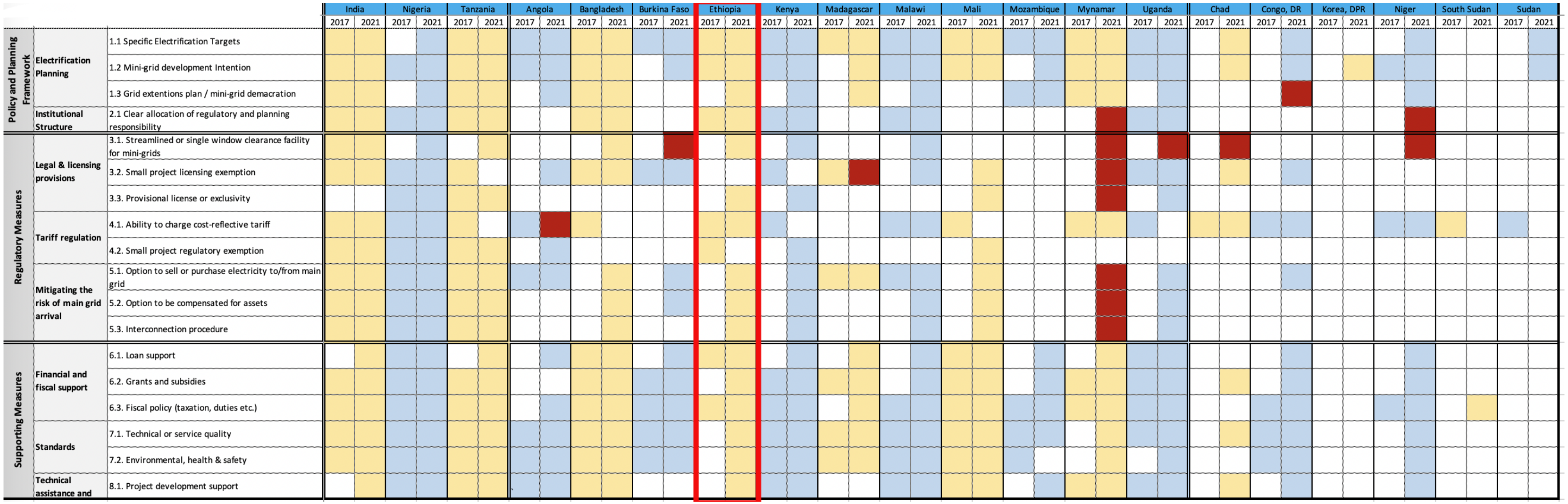

Figure 5: **Evolution of mini-grid regulation in Ethiopia in global context**

Note: Coloured cells indicate the presence of regulatory design features matching the corresponding row description. Red cells indicate data gaps in the assessment undertaken.

Under Ethiopia's NEP 2.0, there are clear plans for the establishment of decentralised electricity infrastructure (including mini-grids and standalone systems) under the country's electrification strategy, and clear roles and responsibilities given to the various government institutions. In the area of regulation, the NEP 2.0 and the country's draft mini-grid directive (see Ahmed *et al.*, 2021) include provisions for the licensing requirements for various mini-grid system sizes and exclusivity on sites for mini-grid developers. Furthermore, there is a commitment to cost-reflective tariffs and regular tariff reviews, but this provision does not have flexibility on project size and scope, as may be useful for smaller projects. Provisions have also been made pertaining to the options available to mini-grids upon future arrival of the grid. To further support the development of the sector, funding and technical assistance are being channelled through active donor organisations in the country, as well as the Rural Electrification Fund.

Despite the above provisions representing much of global best practice, our discussions with local stakeholders revealed several underlying barriers that limit the deployment of decentralised electrification in Ethiopia. The country's public institutions still have limited experience in governing renewable mini-grids and this has slowed progress in the subsector. Governance remains top-down in all areas of the power sector, with MoWIE retaining influence over roles and responsibilities given to other institutions. Thus, given the government's grid-oriented electrification strategy, with mini-grids considered to be transitional, temporary solutions, mini-grids suffer from red tape and limited clarity. Mini-grid developers have experienced difficulty in accessing information on sites preidentified for mini-grid deployment. Cumbersome and lengthy licensing procedures were noted by developers, with concern expressed at the requirement for developers to begin licensing applications only after projects have been completed. These introduce considerable risk for investors, who have noted further discouragement as a result of push-back on exclusivity rights to their projects. With government plans for future grid interconnection where necessary, mini-grid systems are required to meet high standards at higher costs, yet interviewees noted a reluctance from the government to pass on high tariffs to consumers.

These above issues, combined with the negative impacts of the COVID-19 pandemic and ongoing political instability on the sector – in terms of capital inflows, project and legislation delays – meant that some interviewees were pessimistic about the achievement of the country's electrification timetable. Our research suggests that investment in institutional capacity is needed in order that an enabling environment can be fostered for the effective deployment of mini-grids in Ethiopia.

Box III: Key findings on governance of decentralised electrification in Ethiopia

- Since 2017, Ethiopia has added to its regulation of mini-grids, design features that have been utilised successfully in other countries.
- Continued development of mini-grids in Ethiopia could benefit from the introduction of streamlined licensing for smaller projects.
- Stronger institutional capacity is needed to maximise the benefits of established policies, including multi-stakeholder collaboration that builds on experiences and lessons learned from the growing range of off-grid projects in Ethiopia.

The prospects for energy efficient technology use in Ethiopian households

As part of efforts to upgrade the country's power system, the Ethiopian government has been undertaking a reform of its market structures, notably its electricity tariff structures, to ensure electricity production cost recovery. At the same time, the government is pushing for greater energy efficiency in key consuming sectors (EEA, 2019). These progressive activities will have an impact on the manner in which consumers engage with electricity supplied to them. Integrating with other parts of the PATHWAYS project, we sought to investigate the behavioural outcomes of the above activities, and to also explore potential resulting pathways for electricity demand, both at the household level.

Household behaviour responses to energy sector activities

For the investigation of behavioural outcomes, we undertook a telephone survey of 1400 households across urban Ethiopia across July-September 2020 (see Box I). The survey questions were structured so as to understand the role efficient energy behaviour and/or efficient end-use appliances may play, as households respond to increasing electricity prices (beginning in December 2018 with annual increments) and the April-May 2020 lockdown as a result of the COVID-19 pandemic. Further details on the survey methodology can be found in the full report of this work package (Hassen, Seifemichael and Anandarajah, 2021).

Part of the government's energy efficiency program at the household level has included the promotion of efficient technologies for lighting needs, injera baking, and other cooking needs, and the discouragement of inefficient technology adoption. These include the ban on import and sales of incandescent light bulbs since 2011 (EEA, 2019), as well as fully or partially subsidized sales of approximately 9.5 million Compact Fluorescent Lamp (CFL) bulbs between 2009 and 2012 as part of a CFL promotion program (Costolanski *et al.*, 2013). As a result, over 91% of our survey respondents made use of an efficient light bulb (including CFLs), but households still had access to and made use of incandescent light bulbs. Furthermore, 27% of respondents made use of an efficient biomass cookstove, and 34% made use of some other efficient electrical appliance. We found that illegible product descriptions and product affordability issues were key barriers to household uptake of the energy efficient technologies the government is trying to promote.

With electricity tariff increases in 2018, about 30% of respondents indicated that they made no changes to their energy behaviour as a result. Half of the survey respondents indicated that they had become mindful of wasteful usage of electricity. When a service was not in use – such as lighting or television – they were careful to ensure the appliance was switched off. Given the high fuel economy of the electric mitad and electric cookstoves, about 42% of respondents noted that they reduced the frequency with which they used those appliances. Consequently, there was a greater reliance on biomass-based cooking and baking, as 20% of households noted an increased reliance on other fuel sources such as biomass.

Very few households bought energy efficient appliances as a response to higher electricity prices (9%), suggesting increased electricity prices alone were not enough to bring about a higher uptake of efficient energy technologies. During the local lockdown resulting from the COVID-19 pandemic, about 32% of our survey respondents noted an increase in their electricity consumption, less than 1% noted a decrease, and the rest did not observe any change. The vast majority of those that observed an increase in their household's electricity consumption felt it was a result of the extra hours spent at home (94%). Similar to responses to increases in tariff, about 35% of those that noted an increase in their consumption as a result of lockdown became more mindful of wasteful usage of electricity, and 40% of those that noted an increase reduced their use of electric baking and cooking appliances. Further investigation is required to determine the extent to which these short term changes in behaviour during the lockdown had lasting effects on the behaviour of households.

Residential sector electricity demand pathways

Through the Ethiopia Energy Authority (EEA), the government's energy efficiency program also aims to administer Minimum Energy Performance Standards (MEPS) for technologies serving key household services in the near term. Thus, we sought to make use of the pathways developed under this project to explore the potential long-term impacts of MEPS for electricity consuming technologies in Ethiopia's residential sector. We made use of a modelling framework developed by the Lawrence Berkeley National Laboratory (LBNL) for Bottom-up Energy Analysis (BUENAS) (McNeil *et al.*, 2013), and adapted it to explore how residential electricity demand might evolve in the project scenarios with appliance MEPS.

We explored pathways under the New Policies, Ambition, and Slow Down scenarios if MEPS for all household appliances were gradually imposed on the Ethiopian market to full implementation by 2030. We observed a potential 30% in cumulative savings on residential electricity demand between 2017 and 2065 from mandating the sale of energy efficient household technologies. In the Ambition scenario – where growth in household demand is highest – cumulative savings amount to over 1.08 million GWh, or an average of over 22,000 GWh saved per year. To put this into context, Ethiopia's residential electricity demand in 2017 was 5,180 GWh, and in the Ambition scenario reached approximately 128,000 GWh in 2065. A substantial growth in demand, primarily as a result of growth in welfare and wealth of households, but significant savings under a 2030 MEPS for all household appliances. Given the substantial savings possible under the 2030 MEPS – which our analysis showed were not too dissimilar to a 2040 MEPS timeline – we recommend the government's approach to the implementation of appliance standards prioritize rigor for effective implementation, monitoring and enforcement, over speed. As our survey observed, the ban on incandescent light bulbs has gaps in its enforcement. A slower timetable for full implementation of energy performance standards could also ease the appliance cost burden on low-income households, but further analysis would be needed to determine the extent to which this is possible.

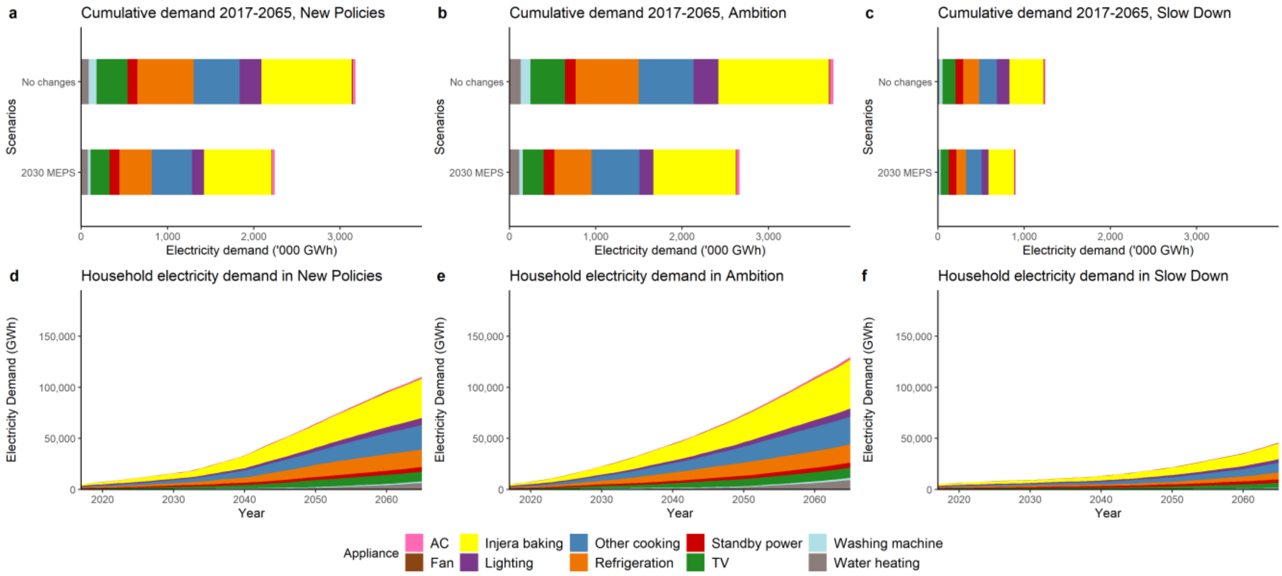

Figure 6: Accumulated household electricity demand with and without 2030 MEPS across scenarios (a-c); Household electricity demand pathway across scenarios (d-f)

Beginning in 2019/2020, the EEA plan to implement MEPS for electrical appliances serving household lighting, injera baking, cooking, refrigeration, clothes washing, air conditioning, and water heating. Detailed plans are in place for the full implementation of standards for lighting for cookstoves by 2020, for by 2025, and for injera baking by 2026, with estimated savings on these appliances by 2030 (EEA, 2019). We explored these plans for the above three appliances in our model to provide further analysis on possible savings. Under the quicker timetable for the full implementation of lighting, baking and cooking electrical appliance standards, almost double the savings possible by 2030 under a 2030 MEPS was observed possible under the EEA's timetable. Our scenarios showed that estimates made by the EEA on possible electricity demand savings by 2030 were probably at their maximum level for cooking, and possibly half of what can be possible from injera baking demand if the future takes the path of the Ambition scenario.

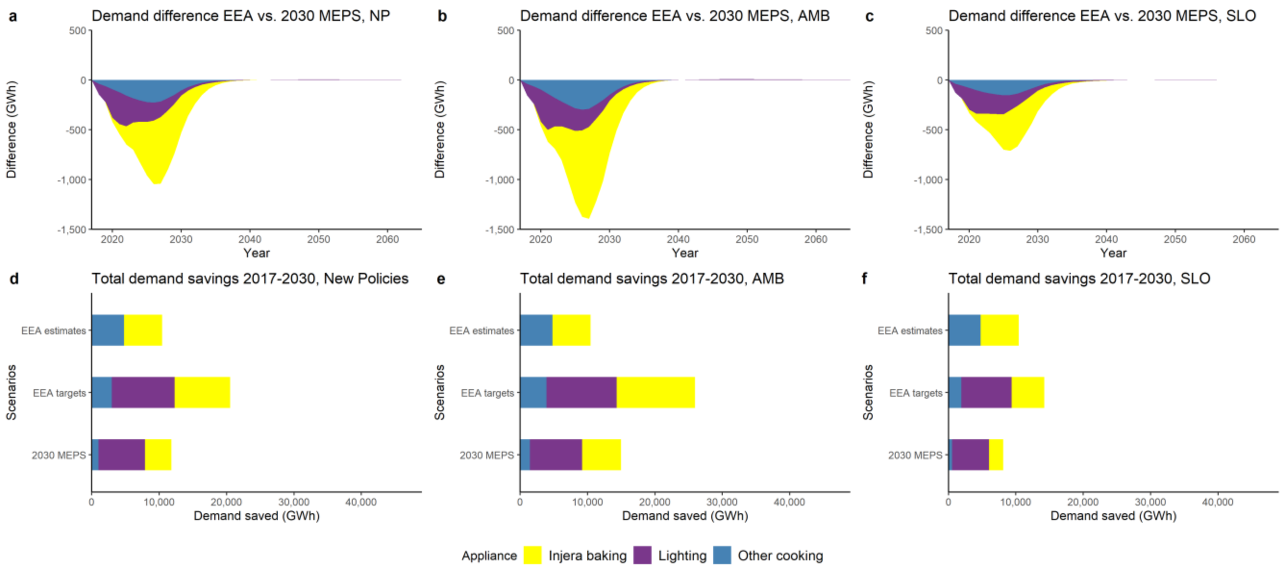

Figure 7: Extra electricity demand saved under EEA timetable compared to 2030 MEPS across scenarios (a-c); EEA timetable comparison of total demand saved by 2030 across scenarios (d-f)

<u>System cost-optimisation with 2030 MEPS</u>

We explored the energy system optimisation models – previously discussed in answers to our first question – using the 2030 MEPS for residential appliances, to identify what impact efficient appliance use in the residential sector can have on the system supply requirements and electrification pathways. This was done for the New Policies, Slow Down, and Big Business scenarios. As can be expected, increasingly lower useful energy demand over time – to various degrees – across these scenarios as a result of efficient technology compared to the base cases (no 2030 MEPS efficiency changes), led to reductions in electricity required from the system, but with some interesting insights at a granular level.

Efficient technology use in the residential sector reduced the required size of the power system in 2065 by 25GW in the New Policies scenario (in installed generating capacity) – reduction of circa 15% compared to the base case. Hydropower capacity installments needed to meet medium term demand growth was down by approximately 5GW till 2045 in the scenario, and importantly, fossil fuel additions required to meet post-2050 demand were considerably lower, by as much as a 9GW reduction in natural gas by 2065 (Figure 8). In the Big Business scenario however – where the pathway for residential demand growth closely follows that of New Policies, but experiences faster and larger growth in the productive sectors, particularly in industry (see reference WP3 report) – there is only a marginal fall in hydro capacity installation over a 10-year period from 2031 compared to the base case. This implies the importance of the built hydropower generators to the overall system from higher demands in productive sectors, since efficiency gains in the residential sector were not enough to substantially decrease the hydro capacity needed, as was the case for the New Policies scenario.

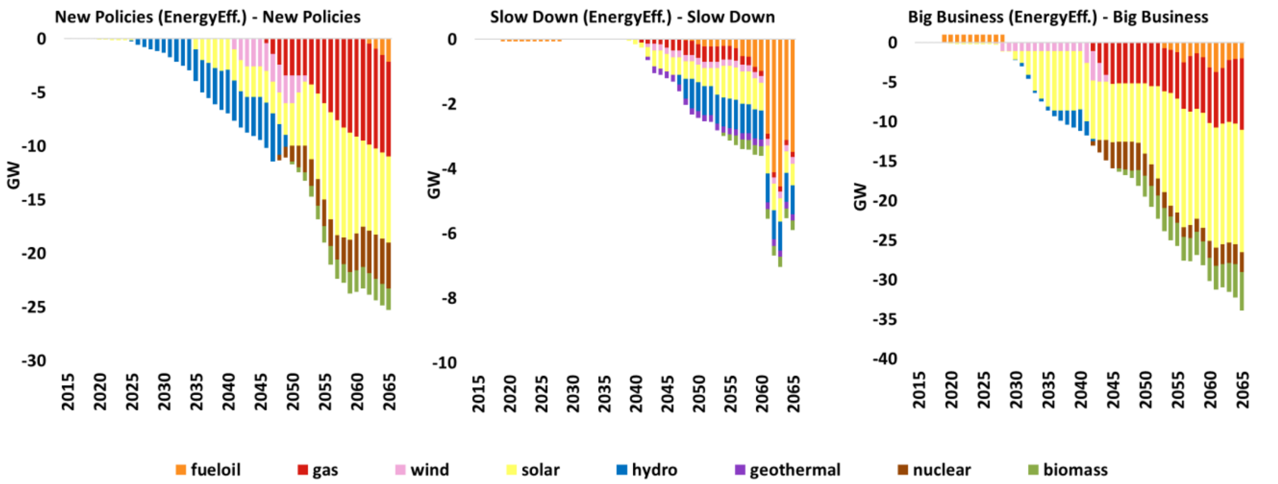

Figure 8: Difference in power generation capacity by fuel, across scenarios (efficiency case minus base case)

Note: Y-axis range is different across the charts in the figure.

In terms of the electricity supply pathways for the efficiency cases, there is a reduction in supply from most technologies where less demand has necessitated less installed capacity and thus, less generation. However, the case of natural gas is an exception, where despite lower installed capacity over time across the efficiency cases of all scenarios when compared with the base cases (as discussed above), there is an increase in generation in the efficiency cases compared with base cases. In the efficiency cases, hydropower reaches its maximum potential later than the base cases. Thus, investments in natural gas capacity – needed to maintain an adequate reserve margin in the power system – take place later. Part of the natural gas capacity is used for domestic consumption, but in the efficiency cases the cost of increasing the operation of gas power plants is lower than export prices, leading to increased operation. This was the case over the medium to long term for the New Policies and Slow Down scenarios.

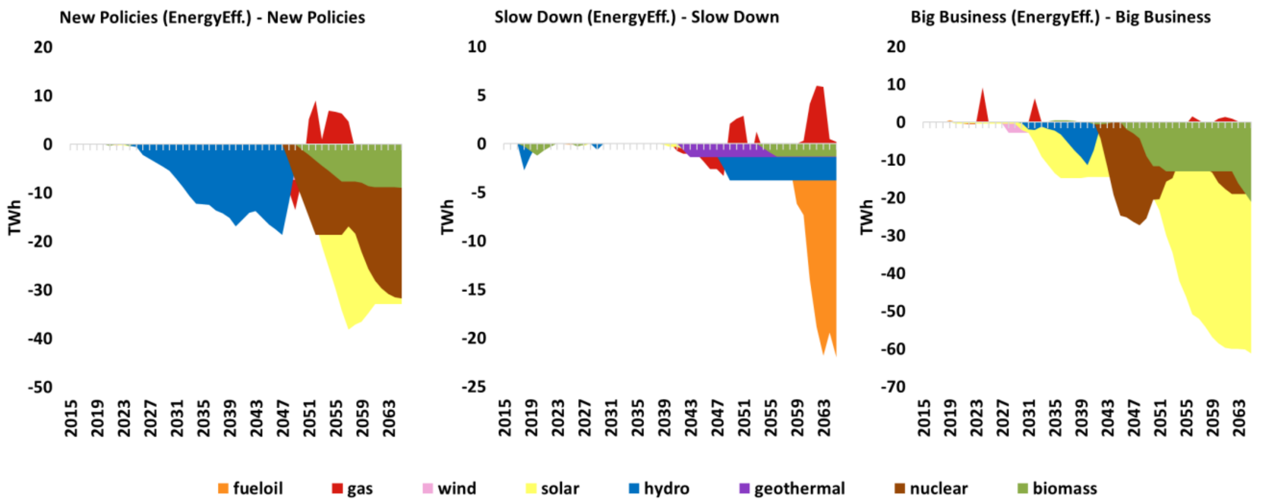

Figure 9: Difference in power supply by fuel, across scenarios (efficiency case minus base case)

Note: Y-axis range is different across the charts in the figure.

With regards to the electrification strategy, the New Policies scenario sees very few changes to electrification technology selection in the face of residential energy efficiency. This was because the New Policies scenario is grid-focused, as prescribed in NEP II. However, in the efficiency case of the Slow Down scenario the number of households cost-optimally served by SHS went up by 9% compared to the base case, primarily shifting from those served by mini-grids in the base case. This difference as a result of energy efficiency primarily takes place after 2060. In the efficiency case of the Big Business scenario, there is a marginal increase in the number of people that are cost-optimally served by SHS – also in the latter years of the scenario – but efficiency gains were not to make notable shifts in the optimal technology type in the years to 2050.

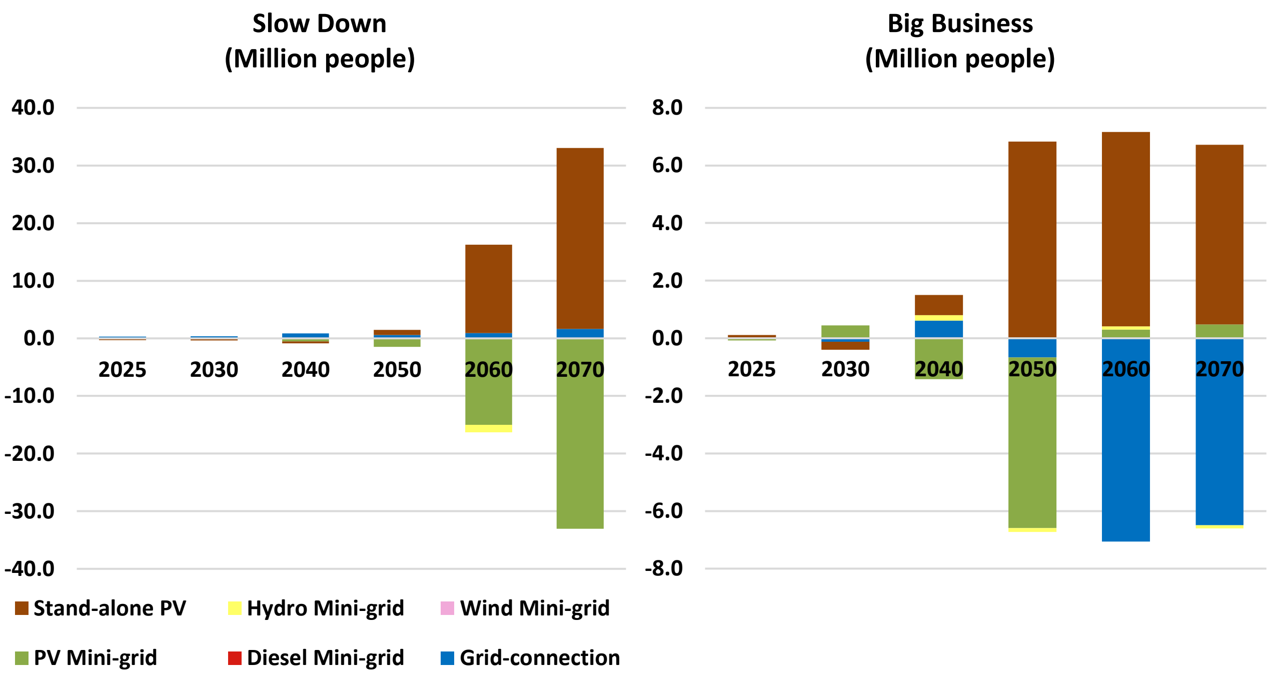

Figure 10: Difference in population connected by technology, across scenarios (efficiency case minus base case)

Note: Y-axis range is different across the charts in the figure.

The transition to efficient technology use in the Residential sector produced significant benefits from a monetary perspective. The resultant decrease in generating capacity requirements meant decreased investment costs, but there was also an increase in revenue due to the increased electricity exports discussed above. Again, this was observed to be the case across all scenarios to various degrees. Generally, the larger the system size for a scenario under the base case, the larger the cost savings observed under the efficiency case. An example of the cost benefits can be seen in the New Policies scenario, where the (undiscounted) cost savings on capital investments over the period 2015-2065 were circa USD 100 billion. This is a reduction of almost one-fifth of the capital investments required in the base case of the New Policies. There was also a USD 12 billion increase in revenue over the period; a 7% increase on the base case.

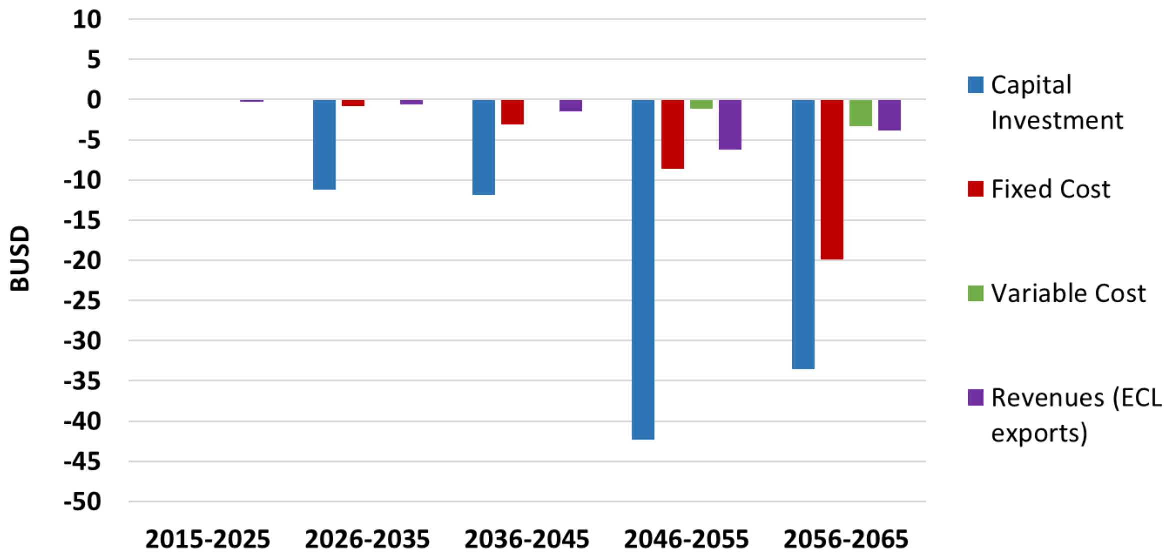

Figure 11: Difference in undiscounted capital costs, fixed and variable operating costs, and revenues for the New Policies scenario (efficiency case minus base case)

Note: Negative "cost" values for revenue indicates positive revenue change.

Box IV: Key findings on efficient technology use in Ethiopian households

- Legible product descriptions and affordability support would enable the uptake of efficient technology.
- Increased electricity bills have primarily meant that some households have reduced wasteful use of energy and decreased their use of electric baking and cooking.
- Full implementation of MEPS by the 2030s can reduce cumulative residential energy consumption by up to 30% by 2065.
- Effective implementation of MEPS should be prioritised over a fast-tracked timetable.
- Full implementation of MEPS in the residential sector alone has the potential to reduce the size of the power system by 15%, reducing capital investment needs by 20%.
- Lower domestic demand from efficient technology can increase electricity exports, raising revenues by 7%.

4 Project Impacts

In addition to the original research outputs broadly covered in the previous section, the development of energy system modelling capacity within Ethiopia was a central aim of this project, which together are expected to foster the long-term development of an ecosystem for strategic energy planning in the country (see Figure 12). Many of the activities to this end, were undertaken as part of the project work and other EEG-funded work, and others have been embedded in ongoing activities of locally-based project partners. We undertook a series of training workshops over the lifetime of the project, and also developed an energy system modelling module within AAiT's MSc programmes. AAiT will be taking on further actions to build the community of energy modellers, and grow the relationship between modellers and planners in the energy sector.

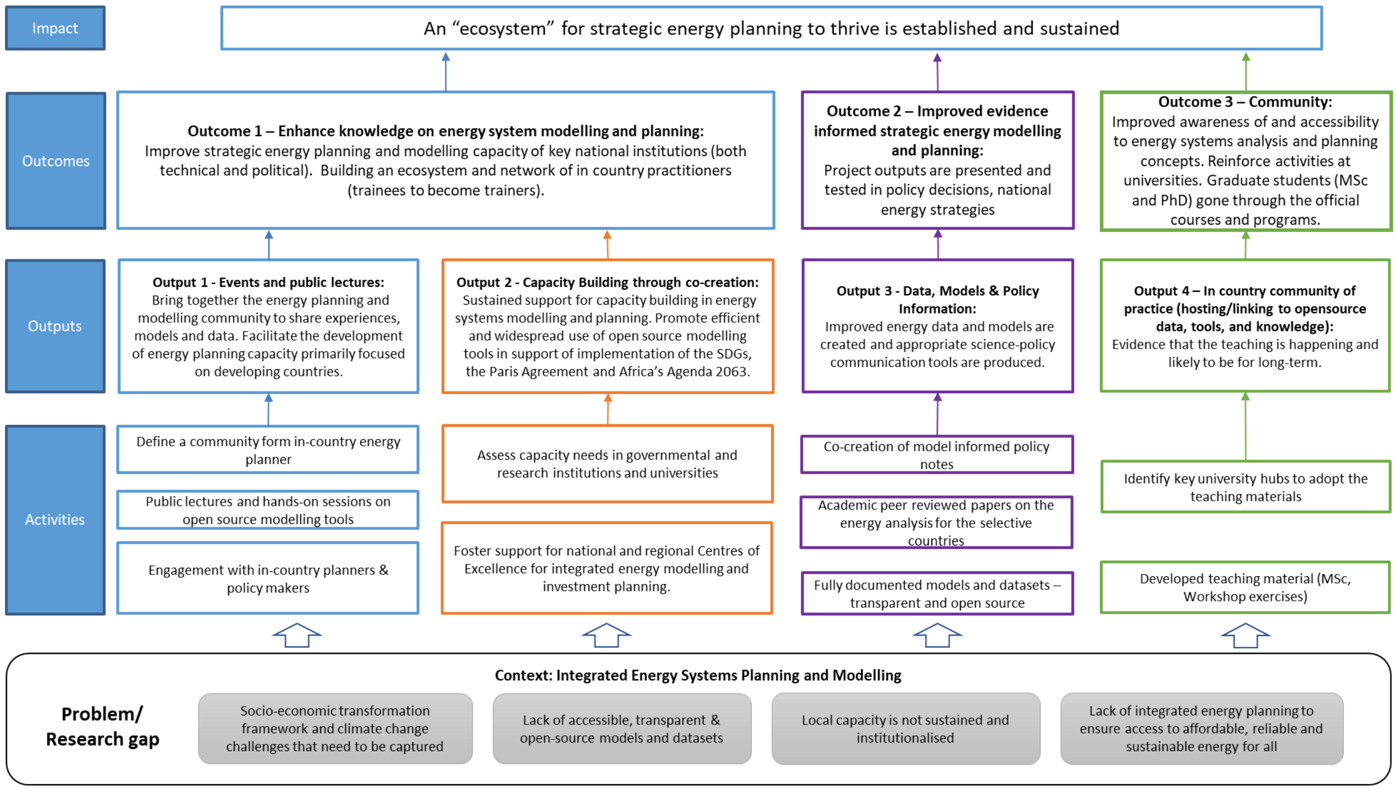

Figure 12: The PATHWAYS project's route to long-term impact

Capacity development activities

We undertook four energy modelling training workshops over the course of the project. The energy modelling capacity development activities were co-led by the KTH and AAiT teams. Given KTH's central involvement in the Open Tools, Integrated Modelling and Upskilling for Sustainable Development (OpTIMUS) community and the various energy modelling training initiatives they undertake as a result (see OpTIMUS), they led the first two 2-day training workshops, with AAiT playing a supporting role. The final two capacity development workshops were led by the AAiT team. This was a key objective of the project (to train the trainers), in enabling the long-term capability for capacity development in-country. Thus, not only were stakeholders trained at the workshops, but the capacity for the AAiT team was developed to be able to undertake training workshops following the completion of the project.

We adopted a comprehensive approach to training that primarily involved hands-on practical exercises related to the Ethiopian context. Consecutive days of training sought to build upon the learnings not only of previous days, but of previous workshops. Thus, we sought to facilitate participant involvement in all workshops, while also enabling the useful involvement of new participants who may not have participated in previous training sessions. Each workshop catered to approximately 20 participants, across government, private sector, and universities. Our approach to capacity development sought to be as inclusive as feasibly possible, however, we were unable to train participants based outside Addis Ababa due to travel and accommodation constraints. In total we trained six women from a total of fourty-six trainees. Through new networks being built between the Ethiopian Women in Energy (EWiEN) association and AAiT, strategic plans have begun to enable increased female participation, as well as enabling the capacity for training workshops led by teams that include female trainers.

An important lesson learnt – during one of many opportunities provided to stakeholders to provide feedback on our activities – is the need to better coordinate training activities with the other external institutions providing the same service locally. Organisations of the United Nations, and other overseas research institutions are responding to the need to build up energy system modelling and planning capacity in Ethiopia under various projects, which is leading to a duplication of activities, disorganised learnings for local trainees, and thus wasted resources. A local centre through which modelling capacity development efforts are channelled through for effective administration is one way of addressing this problem. A three-day knowledge transfer workshop held in October 2019, and funded by EEG, explored the possibility of such as centre, and there were many useful ideas from local stakeholders, which would need funding support to establish. Initiatives such as EEG's "Principles" for supporting strategic energy planning, will also be a useful platform to draw on for coordinated capacity development (OPM, 2020).

<u>Dissemination</u>
We disseminated our project outputs to local and international audiences in three main ways: conference presentations, policy briefs, and scientific journal publications. The project outputs were presented at local and international conferences. A total of four presentations were delivered in June 2021 at the International Energy Workshop and the conference of the International Association for Energy Economics. In partnership with the Ethiopian Economics Association, the project hosted a half-day session at the association's 2021 conference, where project outputs and insights were presented to conference attendees that included government officials, students, academics, and other professionals. Outputs of the project have been published in the scientific journal Energies (Pappis *et al.*, 2021), and further publications of the project outputs are under review in leading academic journals. Three policy briefs aimed at policy makers were also published and presented to stakeholders at dedicated workshops.

5 Conclusions and Future work

The PATHWAYS project has found that it is important for Ethiopia to make plans for the diversification of its power generation sources away from a dominant reliance on hydropower, if it is to secure the long-term supply of electricity that will be needed under the country's growth ambitions. Intermittent renewables have an important role in the future system, and our scenarios suggest probable higher reliance on fossil fuels. Our findings are in line with the government's plans to draw on mini-grid and off-grid systems as part of its electrification strategy. However, our scenarios show there is merit in allowing system choice to be determined by the expected spatial growth of electricity demand, which may not require mini-grid and off-grid systems to play a temporary role in the future of the country's power sector. Efficient consumer technology has the potential to considerably reduce the burden on Ethiopia's electricity system, and effective implementation of policies to foster a high market composition of efficient user-friendly technologies will be an important enabler of uptake. This effective implementation of policies will need to be aided by strengthening local institutions, as revealed by our investigation into the regulation and governance of renewable mini-grids in the country.

The benefit of energy system modelling for policy and planning support is found in timely and periodic exploration of possible futures as the circumstances facing the power system and sector structures continue to evolve. Our capacity development activities have laid the foundation for Ethiopia's modellers, researchers, students, and government staff to advance the work started by our research project. Some specific areas of useful further work include:

- Modelling medium to long term implications of droughts on system security, given heavy reliance on hydropower.
- Development of a Climate, Land-use, Energy and Water Systems (CLEWs) model for Ethiopia, to explore the implications of future technology mixes suggested possible in this work e.g., introduction of biomass-based electricity generation.
- Long-term achievement of Ethiopia's Nationally Determined Contributions (NDCs) with the potential need for greater reliance on fossil fuel-based electricity generation.
- Incorporation of non-domestic energy consumers, such as hospitals, small and medium sized enterprises (SMEs), irrigated agriculture, into the electricity demands considered in Ethiopia's geospatial electrification (OnSSET) model.
- Investigation of lasting consumer energy behaviour changes resulting from the 2020 COVID-19 lockdown.
- Incorporating an analysis of the long-term cost to consumers of the appliance energy efficiency standards explored in the LEAP model of Ethiopia's residential sector.

Other projects of the EEG programme in Ethiopia have also undertaken research that can closely inform some of the future work identified above, particularly around data. There are immediate actions that should be taken to boost the impact of the PATHWAYS project; steps that will require funding, such as the establishment of a local energy system modelling centre to administer and manage the development of the modelling community. The government of Ethiopia, through MoWIE – and in partnership with its international partners, such as EEG – should be encouraged to build on the success of the PATHWAYS project.

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