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Universal access to electricity: actions to avoid locking-in unsustainable technology choices

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1. Introduction

In 2015, the United Nations' sustainable development goals (SDGs) were approved. They lay out a shared vision to 2030 for 17 key developmental concerns. SDG7 targets access to affordable, reliable and modern energy services for all; SDG13 focuses on reducing greenhouse-gas emissions and adaption to the impacts of climate change (United Nations 2015). Efforts to achieve SDG7 and SDG13 are interlinked, in that fossil fuels will be used, to a greater or lesser extent, to expand access to modern energy services in developing countries. The dominating view is that the economics of rural-electrification projects are such that these projects, to a high degree, have to rely on fossil fuels. Yet, the literature is inconclusive on this point.

Two main studies explore the synergies and trade-offs associated with efforts to achieve SDG7 vis-à-vis the remaining sustainable development goals (Fuso Nerini *et al* 2018) (Mccollum *et al* 2016). Both studies conclude that the synergies outweigh the trade-offs, and call for increased policy coherence. However, studies that explore specifically the trade-offs associated with achieving the universal electrification elements in SDG7 and the climate change-mitigation elements in SDG13 are scarce, and their findings are inconsistent:

- Some of these studies find that synergies outweigh trade-offs. For example, the International Energy Agency (2017) reports that universal access to electricity by 2030 would increase carbon-dioxide emissions by a mere 0.7%, compared to a reference scenario. Similarly, a study focused on India (Pachauri 2014) concludes that rising electricity access rates would have little impact on greenhouse-gas emissions, as does a study focused on Rwanda (Bisaga *et al* 2021).
- A number of studies reach the opposite conclusion: trade-offs outweigh synergies. For example, Moss and Leo (2014) conclude that, for a set budget, and compared to using exclusively renewable energy, relying on a mix dominated by natural gas can expand electrification in sub-Saharan Africa by an additional 60 million people. In a similar vein, Dagnachew *et al* (2018) find that climate change mitigation policies increase electricity prices, implying that the electrification rates that can be achieved through renewable energy-powered electricity generation are comparatively lower. A study by Koçak *et al* (2019) reaches similar conclusions.

Research on the extent to which oil prices affect the fuel mix (and, thereby, greenhouse-gas emission levels) is equally inconclusive. McCollum *et al* (2016) found that 'sustained low or high oil prices could have a major impact on the global energy system over the next several decades' and note that 'the carbon dioxide consequences could be significant'. In contrast, the International Energy Agency finds that low oil prices would only increase greenhouse-gas emissions slightly (IEA and IEA International Energy Agency 2011).

Notwithstanding, two aspects of universal electrification are clear. Firstly, under current conditions (namely, low oil prices and high interest rates for renewable energy-powered electricity-generation projects), fast-track electrification (Alstone *et al* 2015) is likely to rely on carbon-intensive technologies, because they have the lowest up-front costs. Secondly, relying on fossil fuel-powered electricity generation will lock-in the associated carbon-dioxide emissions and higher costs (operation and maintenance costs, and fuel costs) for the entire life-time of the technology used, because an externality like global warming will not persuade investors to forego their expected returns on investment.

In light of the above, this article makes the case for renewable energy-powered rural electrification, and against fossil fuel-powered technologies. It does so by quantifying the magnitude to which regulating the price of diesel—through subsidies and taxes—affects two sets of parameters: the extent and cost of electrification programmes, and the greenhouse-gas emissions associated with the implementation of these programmes. The analysis, based on high-resolution geo-referenced modelling, covers 71 countries in Africa, South Asia and developing East Asia, representing 85% of the world's un-electrified population.

The importance of making this case cannot be understated. Indeed, universal electrification and climate-change mitigation are mutually supporting goals that cannot be achieved independently from one another (Johansson *et al* 2012).

2. Fast-track electrification pathways

Against the background presented above, the need to weigh the trade-offs between the pace and the cost of electrification programmes becomes self-evident. The following paragraphs introduce a geo-referenced computer-based model that facilitates this task. For more details on the model, please refer to Szabó *et al* (2021), including its supplementary materials note.

Within a one-square kilometre grid, the model spatially quantifies the extent to which regulating the price of diesel (through subsidies and taxes) affects three sets of parameters: population coverage, cost of electrification programmes, and the greenhouse-gas emissions associated with the implementation of these programmes. The analysis covers 71 countries in Africa, South Asia and developing East Asia (Szabó *et al* 2021), which are home to 85% of the world's un-electrified population. The model and its assumptions build on the authors' activities over the past decade (Szabó *et al* 2011, 2013, 2016, 2021), focused on mapping off-grid electrification options in Africa, and advising African governments and development aid agencies in this area. Specifically, the model relies on the methodology presented in a 2021 study (Szabó *et al* 2021).

For the two dominant off-grid technologies (solar photovoltaic and diesel), and separately for three socio-economic scenarios, the model calculates site-specific electricity costs, based on which a least-cost option is selected for each of the geo-referenced cells. This makes it possible to calculate, for the (modelled) un-electrified households in each cell, both the investment costs required to support full electrification for residential use and the resulting carbon-dioxide emissions (Szabó *et al* 2011, 2013, 2016, 2021).

Model runs are consistent with three of the latest socio-economic scenarios by the Intergovernmental Panel on Climate Change, the so-called shared socioeconomic pathways (SSPs) (O'Neill *et al* 2017, Riahi *et al* 2017):

(a) Sustainable development scenario: this scenario is consistent with SSP1, in which high fossil-fuel prices prevail. Electricity generation is powered by renewable sources of energy, with solar photovoltaic dominating off-grid electrification technologies. In this scenario, 2021 national retail prices for diesel are considered representative of the first half of the decade. (During this period, diesel prices were stable at a high level and reached the highest value of 2010–2020 in February 2012. National-level taxes and subsidies are included in national diesel prices.)

(b) Conventional development scenario: this scenario is consistent with SSP5. Fossil fuels are cheap, with no resource constrains, and diesel generators dominate off-grid electrification technologies. To replicate this conditions, the February 2016 retail fuel prices per country were selected as input to the model. During this time, one of the lowest price levels in the decade was registered, when the price of Brent fell to around US$29 per barrel.

(c) Locked-in technology scenario: this scenario is consistent with SSP3, and assumes continued oil price volatility. Diesel becomes the least-cost alternative for a growing share of the population. Investments decisions are based on short-term price signals. To replicate the low diesel price, and as in the previous scenario, the February 2016 retail fuel prices per country were selected. Once the investment in diesel systems is made, its extended use leads to spikes in demand and, ultimately, to fuel-price increases. To this, high and stable 2012 prices were used.

For each of the three scenarios considered, the panels in figure 1 plot the differences between solar- and diesel-based electricity production cost at one square-kilometre resolution, with cheaper solar photovoltaic depicted in red, and cheaper diesel depicted in blue. The higher the contrast, the larger the difference in costs.

Figure 1 illustrates that, in North Africa, where diesel is heavily subsidised, diesel becomes the most competitive option, irrespective of the scenario chosen. In contrast, in Easter Africa and Madagascar, where subsidies for diesel are lacking, renewable energy-powered systems become more competitive, especially in the scenario that assumes high diesel prices. In short, our model results are consistent with the well-established notion that fossil-fuel

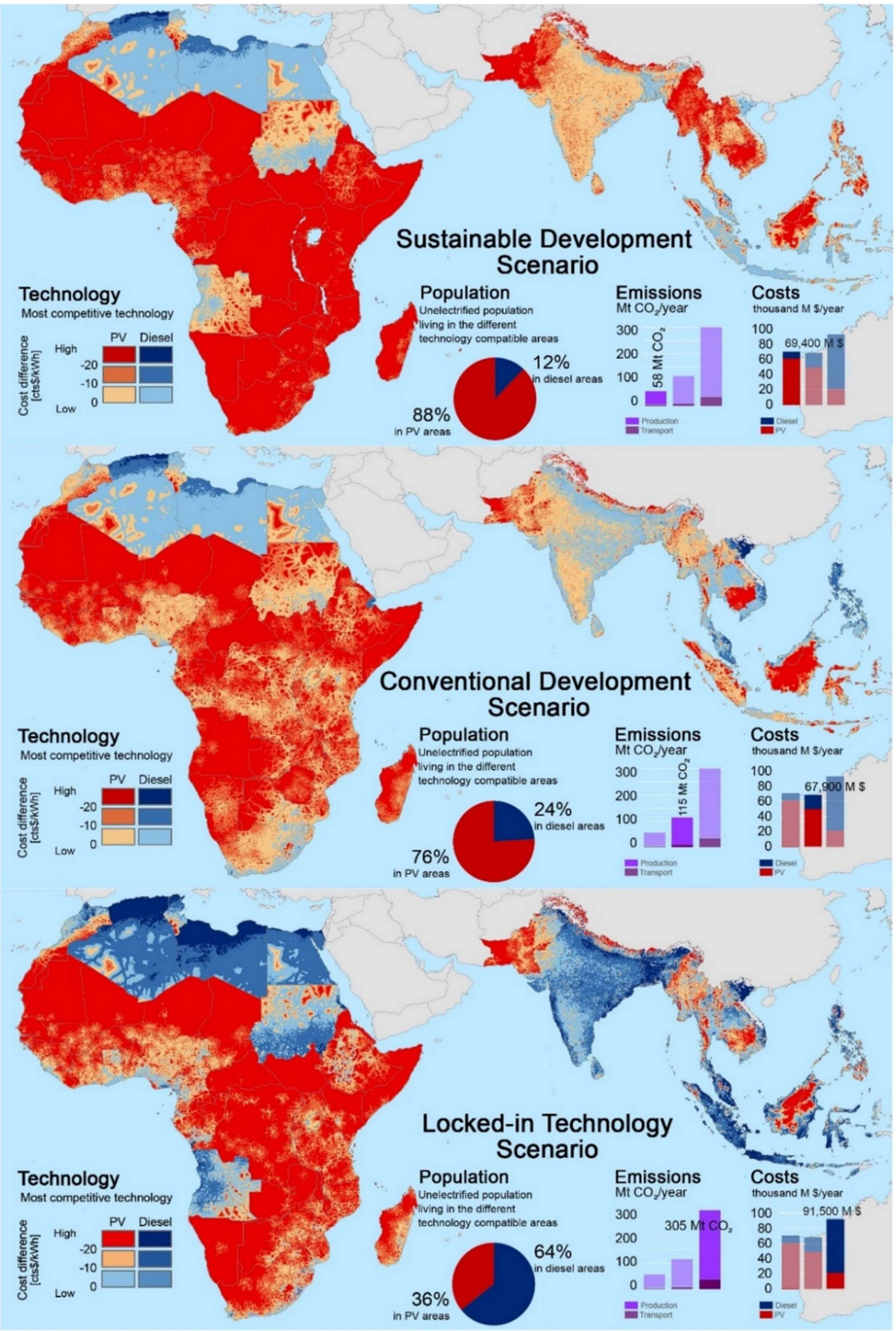

Figure 1. Location-specific estimates of the relative electricity costs (¢USD/kWh) of solar photovoltaic versus diesel. The pie chart depicts the share of population currently lacking access to electricity that rely on solar photovoltaic (red) versus diesel (blue) to generate electricity. The stacked column charts compare the associated greenhouse-gas emission levels for the three SSPs (left-hand side), and annual costs of electrification (right-hand side).
Source: the maps were generated using the following data, collected and processed by the authors: GHS population grid—GHS-POP (European Commission Joint Research Centre (JRC) and Columbia University Center for International Earth Science Information Network (CIESIN) 2015) data, produced and made publicly available by the European Commission—JRC (https://ghsl.jrc.ec.europa.eu/data.php); Nighttime lights Version 4 DMSP-OLS (US NOAA National Oceanic and Atmospheric Administration -National Geophysical Data Center and US Air Force Weather Agency 2014), produced and made publicly available by NOAA's National Geophysical Data Center (https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html); the Electrification access rates (The World Bank 2017) (EG.ELC.ACCS.ZS) made publicly available by the World Bank through The Open Data Portal (https://data.worldbank.org); and Electricity Grid Vector data publicly available by several sources (National Renewable Energy Laboratory (NREL) and National Renewable Energy Laboratory 2015; OpenStreetMap Foundation (OSMF) and Contributors 2021) (OpenStreetMap, www.openstreetmap.org/, NREL—Geospatial Toolkit www.nrel.gov/international/geospatial_toolkits.html and EnergyData https://energydata.info). The spatial classification was made and mapped using ArcGIS 10.6 (https://desktop.arcgis.com/). GIMP 2.10 (www.gimp.org) was used for image editing.

Table 1. Share of population without access to electricity relying on diesel, associated carbon-dioxide emissions, and annual costs, by scenario.

	Share of un-electrified population that would rely on diesel generators		Associated annual carbon-dioxide emissions	Associated annual costs
Scenario	Percent	Million people	$MtCO_2$	Billion USD
Sustainable development	12	150	58	69.4
Conventional development	24	298	115	67.9
Locked-in technology	64	797	305	91.5

Source: study calculations based on methodology described in detail in (Szabó *et al* 2021).

subsidies hamper the deployment of renewable energy-powered electrification options—and it corroborates this finding through geo-referenced estimates of a resolution previously unavailable. In addition, figure 1 illustrates the implications of taking a short-term view on decisions concerning the choice of electrification technology. Simply stated, a country that invests massively in diesel, mainly as a reaction to low fossil-fuel prices, will be exposed to the impacts of oil-price volatility. Angola, India and Indonesia are cases in point: our locked-in technology scenario shows the magnitude of the impacts associated with oil-price volatility. In this context, note that the areas coloured in light orange or light blue, namely those where the price gap between fossil—and non-fossil—fuelled technologies are smallest, are especially sensitive to regulation.

The model runs with one boundary condition—full electrification by 2030—and two key assumptions: investment decisions are made over the following couple of years, and benefit from a high share of public finance. Not least, the model does not consider endogenous technological change at any time within the period considered and, for this reason, technology choices remain unchanged.

For each of the three scenarios, annual investment costs and carbon-dioxide emissions associated with the provision of universal access to electricity by 2030 are estimated (Szabó *et al* 2021). Table 1 gives a summary of the various estimates.

The estimates associated with the sustainable development scenario (table 1) reveal that full electrification entails a marginal (1.5%) increase in carbon-dioxide emissions. This finding is consistent with the results of the analysis (IEA and IEA International Energy Agency 2011) referred to above[3]. Specifically, for each of the three scenarios listed in table 1, the increases in carbon-dioxide emissions are, respectively, 0.2%, 0.5% and 0.9% compared to a scenario with no increase in electrification.

The estimates associated with the conventional development scenario (table 1) highlight that, if cost-efficiency remains the decision-making criterion and short-term price signals are followed, compared to the sustainable development scenario annual investments decrease by less than 3%. Carbon-dioxide emissions and the share of population electrified with diesel double.

Finally, the estimates of carbon-dioxide emissions and cost levels associated with the locked-in technology scenario (table 1) suggest that emission levels under this scenario would grow by a factor of 5.3 compared to the emission levels associated with the sustainable development scenario. Crucially, under the locked-in technology scenario, annual costs are highest, and average costs per kWh (which eventually are reflected in user prices) are also highest (figure 2). Large part of these costs come from the operation costs that is fully borne by the users so this scenario entails the highest risks of disruptions. For details on the model, please refer to Szabó *et al* (2021), including its supplementary material.

The locked-in technology scenario reflects the financial conditions that prevail in most countries with low electrification rates. In other words, this scenario illustrates the probable electrification pathway that, without policy intervention, these countries are likely to follow—one that punishes newly electrified users and society more broadly, as described above, and one that makes energy access and climate-change mitigation goals incompatible. Policy intervention can help steer electricity markets away from this path, and toward a path that is closer to that characterised in the sustainable development scenario, where energy access and climate change mitigation goals can be achieved simultaneously.

[3] The International Energy Agency considers marginal diesel use and low electricity consumption (365 kWh/year/household) for the residential sector. Increasing the residential consumption to 1250 kWh/year/household, results in a 4% growth in emission levels. In this context, it is worth noting that recent experiences in Kenya, Burkina Faso and Tanzania have shown that the residential sector represents less than 40% of the overall consumption for off-grid systems. Accordingly, when accounting also for the consumption of productive use, total carbon-dioxide emissions would increase more than twofold.

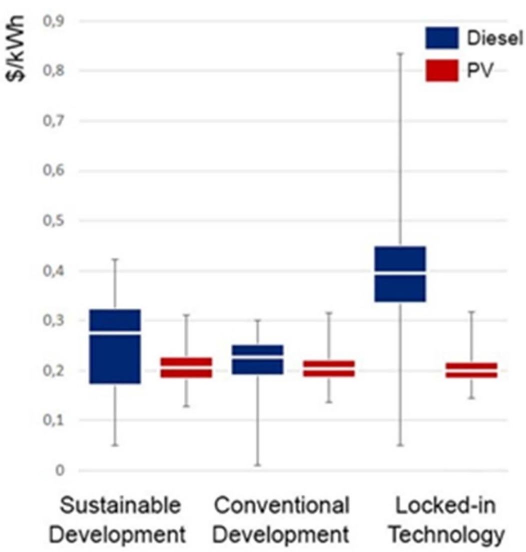

Figure 2. Estimates of electricity costs (in USD/kWh), by technology and scenario The figure shows a box-and-whisker plot of average electricity cost values in each of the 71 countries studied, per scenario and technology (diesel or PV). The box is delimited by the lower and upper quartiles, the median is marked by the white line, and the whiskers represent minimum and maximum estimates. Compared to PV costs, the diesel costs show higher dispersion in the three scenarios. In the case of the locked-in technology scenario, more than three quarters of the values are higher than the maximum PV cost. Source: study calculations based on methodology described in detail in (Szabó *et al*2021). The spatial statistics were calculated using ArcGIS 10.6 (https://desktop.arcgis.com/).

3. Actions to avoid locking-in unsustainable technologies

It follows from the findings presented in the previous section that, when cost, emissions, and distributional impacts are factored in, over a period of time spanning at least one decade, the public-policy options encapsulated in the sustainable development scenario represent a more beneficial solution for society as a whole. Nonetheless, decision makers may be reluctant to pursue those policy options, because they challenge established balances of power, and their full benefits only accrue within a time period that goes well beyond electoral cycles. Although a classic political-economy dilemma, the solution to breaking this vicious circle is far from simple.

Through low oil prices and high interest rates on renewable energy-powered electricity-generation projects in developing countries, unregulated markets will continue to favour fossil fuels. What is more, paradoxical as it may be, investment in fossil fuel-powered electricity generation will be justified on developmental grounds. Yet, as the analysis presented in this article underscores, inclusive development that is truly sustainable in the long-term calls for halting fossil fuel-powered electricity generation, and expanding renewable energy-powered solutions. No silver bullet exists to achieve this goal, as solutions will require adaptation to local conditions. Nonetheless, a moratorium on new fossil fuel-powered electrification projects may provide a suitable policy framework internationally, under which appropriate local solutions can be framed. Such a moratorium would also have to apply to development aid-funded projects, the investments of which would reap two types of benefits: greater public-good provision in terms of increased greenhouse-gas mitigation, and sounder long-term economic rationale for investments, thus boosting aid effectiveness.

The results of our analysis show the need for improved coordination among countries and international financial institutions. Such coordination would help implement a regulated approach to investment in electrification programmes across all regions—one that could halt investments in large carbon-intensive power plants. Not least, such coordinated approach would go beyond supporting climate change-mitigation targets: it would also decrease the consumers' burden, compared to the prices that consumers would face in the locked-in technology scenario. A paradigm shift in this direction would help offset the negative trade-offs between least-cost electrification options (namely low-cost diesel) and options that are consistent with climate change mitigation goals (namely solar photovoltaic). Although this is certainly a tall order, the rewards associated with realising it are undoubtedly worth the effort.

The Development Assistance Committee, under the Organisation for Economic Cooperation and Development, is well positioned to orchestrate the moratorium referred to above among development-aid agencies. However, given that development aid agencies are but one of several actors in the area of electrification, an agency with a broader remit—one that involves all relevant actors—should lead the way. Arguably, the sustainable energy for all initiative is the most appropriate instrument through which the terms of a moratorium on new fossil fuelled-powered electrification could be agreed (Puig *et al* 2021).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the Technical University of Denmark or the European Commission.

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