# High-resolution Global Pathways to Achieve 100% Electricity Access in 2030

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# Abstract

Universal access to electricity is a crucial component of achieving the sustainable development goals. However, model projections suggest that under current policies, this goal will not be reached by 2030. There is still little understanding of electrification strategies and investment needs across global regions. To address this gap, we explore scenarios for achieving universal access globally, considering decent living standards and synergies with climate change mitigation. The analysis integrates high-resolution population GIS data with socioeconomic and energy system data from the integrated assessment model IMAGE to analyse the least-cost optimised pathways for universal access by 2030. The results indicate that universal access requires an additional investment of around 19 billion USD annually, with renewable off-grid systems playing a major role. Combining universal access with climate mitigation policies would require 15% more investment but would reduce $CO_2$ emissions by nearly 30% relative to the default electrification scenario.


# Little is known about electrification strategies at the global level

There are 770 million people without access to electricity globally, of which 77% live in Sub-Sahara Africa (SSA) [1]. If the current electrification trends continue, IEA projections indicate that by 2030, 670 million people will not have electricity [1], meaning that the Sustainable Development Goal (SDG7.1) of universal electricity access will not be achieved. In fact, the progress in electrification has slowed down in recent years because of the increasing complexity of reaching more remote and poorer areas and the effect of the COVID-19 pandemic [2].

Most research to achieve SDG7.1 is focused on SSA [3–6], given the dominance in the number of people lacking access. For instance, Dagnachew et al.(2017) concluded that off-grid systems are the least-cost option for up to 65% of the SSA population gaining access between 2010 and 2030. While over 100 million people still lack access outside this region, only a few studies focus on specific countries outside SSA [7–9]. Furthermore, a global overview of electrification strategies is missing, which is important to get a perspective on the overall investment need and the similarities and differences in electrification strategy in different parts of the world, and that would put the SSA efforts in perspective [10].

One of the studies that looked at the global perspective, Van Ruijven et al. (2012), analysed electrification investment of grid extension for rural areas globally using the IMAGE model [11] and by constructing regional cost curves of marginal electrification cost from grid extension obtained from a spatial analysis (resolution of 30’x30’). Pachauri et al. (2013) [5] conducted a model comparison analysis for electrification globally using IMAGE and MESSAGE, looking mostly at grid extension combined with a post-processing analysis. They estimate the additional capacity for universal access (UA) with central grid extension of all rural houses to be between 21GW and 28GW (between 2010 and 2030). Panos et al. [12] analysed electrification under two pathways using the GMM partial equilibrium energy model, indicating that an increase in power capacity of 133 GW or 192GW is needed from their base-case scenario with an undiscounted investment of $36B and $49B. However, the low geographic resolution of GMM (15 world regions) does not enable the analysis of the least-cost options. For example, the share of off-grid renewable technologies obtained cannot consider local energy resource potential and electricity demand, and the cost of a new distribution network cannot consider local population density.

In the assessment of electricity access worldwide, it is important to cover the local context as, for instance, the cost of in-situ systems depends on the spatial spread of households, local energy demand and resource availability [13]. Furthermore, combining high-resolution (HR) spatial assessment with integrated global analysis can provide better insight into the possible trade-offs and synergies between universal electricity access and climate change mitigation. It is also critical to look at the provision of enough electricity to cover all essential needs. Electricity access can be expressed in tiers as defined by the World-Bank Multi-Tier Framework [14], going from tier 1 (sufficient for a few hours of lighting, phone charging and radio) to tier 5 (capacity sufficient for air conditioner, refrigerator, ironing, washing machine, among others. ). In some cases, current access in SSA can only cover tier 1 demand level [2]. Although achieving Tier 1 access can be a catapult to better lives, it is still insufficient to cover all needs for a decent living. In this research, we implement the definition given by Rao & Min [15] with a focus on the appliances needed in the household to have a decent life. They are access to refrigerators, lighting, modern cooling if needed, one phone per household, one television or computer monitor, and one washing machine per household [15].

With this research, we add to the existing literature by conducting an updated integrated analysis to explore the least-cost strategies for achieving universal electricity access globally by 2030 compared to 2020 access rates, the consideration of decent living, the investment needed, and the synergies with climate change mitigation. We analyse differences across the regions and for the world, considering both global trends and local spatially detailed parameters that can influence the electrification process. For this, we build upon the work of Dagnachew et al. for SSA [4] and expand the geographic scope to the global level. Furthermore, the electricity access model is updated and re-coded for open-source access, and the spatial resolution has been increased from 30’x30’ to 5’x 5’. This model is soft-linked with the integrated assessment model IMAGE for implementing regional socioeconomic data scenario projections and for assessing the climate impact of universal access strategies. The levelized cost (LCOE) for plausible electrification solutions is assessed per grid cell worldwide to select the least-cost option. They are grouped into central grid extension and two off-grid options, mini-grids and stand-alone systems. The stand-alone systems include solar home systems and diesel generators. The mini-grids considered are sourced by wind and PV backed up by batteries, mini-hydropower, diesel, and PV and wind combined with diesel.

Our results indicate that off-grid systems are the least-cost solution for most people gaining access from 2020, and an additional investment of at least 19 billion USD annually is needed to achieve UA by 2030. The additional investment amounts to 100 billion USD annually to ensure UA to minimum decent living levels. Furthermore, achieving UA with climate policies in place results in a reduction of electricity-related residential $CO_2$ emissions of nearly 30% with 15% of additional investment compared to the UA scenarios without climate mitigation.

# Main

## Baseline development is not enough

In the baseline scenario, based on the middle-of-the-road projection of the Shared Socioeconomic Pathways (SSP2), electrification rate projections are driven by income growth, population density and urbanisation trends. The modelled rates are calibrated with historical data until 2020. Under this scenario, India, North Africa, and South America (excluding Brazil) achieve universal access before 2030. (see Figure A1 in appendices). At the same time, over 650 million people could still lack access by 2030, and 91% of them could be in Sub-Saharan Africa. In fact, full electrification under this scenario would only be achieved by 2080.

It should be noted that while this scenario does not achieve SDG7.1, the projected investment in the power sector is significant for the global regions currently lacking access (white areas in Figure 1), as 94 billion USD annually are estimated to be invested between 2020 and 2030. It is mainly led by an increase in demand due to population and household electricity demand growth within currently electrified grid cells. Note that only 20% of this projected investment is dedicated to SSA, where the access deficit is the largest. This results from the relatively low household demand levels projected for SSA and the low progress on electrification in this scenario, with projected average access rates in the region just under 70% by 2030.

## Achieving universal access

As an alternative to the baseline, we look at four scenarios to analyse how to achieve universal access (UA) to electricity by 2030. All are based on linear growth of the electrification rate between 2020 and 2030. However, they differ in two dimensions: the level of household electricity demand achieved and the presence of climate mitigation policies. For the first dimension, two levels of household electricity demand are implemented. First, a baseline household demand is implemented obtained from the SSP2 baseline scenario as modelled in IMAGE (per region and for urban and rural quantiles), and second, the decent living standard (DLS) demand, which is also based on the SSP2 baseline but implements a minimum threshold demand level to ensure a DLS for each household. I.e., ensures access to basic appliances (cooling, refrigeration, lighting, etc. See methods). This DLS demand threshold can vary per region and for urban and rural areas due to variations in cooling needs, as calculated by Mastrucci et al., 2019 [16]. The second dimension allows us to analyse the impact of climate policies. For the climate policies scenarios, a climate mitigation scenario from the NAVIGATE project was used [17]. It limits global warming to below 2°C with a maximum $CO_2$ emissions budget of 1150Gt between 2020 to 2100. The main mitigation instruments the scenario applies are implementing a carbon tax for all regions and using advanced mitigation technologies in producing sectors favouring renewable energy deployment. As a result, the scenario projects high penetration levels of wind and solar sources in the power mix and high electrification levels in the industry, building and transport sectors.

In all scenarios, we compare different options to provide full access to electricity – either through grid extension, six mini-grid solutions or stand-alone systems. The latter two options are sourced by renewables or diesel, or a combination of both for two mini-grids (wind with diesel or PV with diesel). The calculations consider the electricity demand density, distance to the existing grid, and local production costs. The model determines the least-cost option for electricity access by comparing the total LCOE of all available technologies for each map grid cell. Within 50 km of the existing central grid network, the model automatically chooses the central grid as the preferred technology to avoid revenue risk for off-grid operators. The maps in Figure 1 show the locations where central-grid extension, mini-grid connections or stand-alone systems are chosen as the least-cost options over three scenarios, while Figure 2 shows the optimised distributions of the nine options considered over the population gaining access between 2020 and 2030 for all four scenarios.

Results for the first UA scenario without climate policies and with baseline demand (SSP2-UA) show that stand-alone (SA) systems and central grid extension are favoured for most locations (Figure 1-a). Solar photovoltaic is the least cost-option for all SA systems selected (except in Indonesia). Note that although SA systems are selected for large areas of low population, mini-grids, mainly those sourced by PV or PV diesel combined, are the least-cost options for most people gaining access with off-grid solutions (Figure 2). The climate policies implemented in the SSP2-2C-UA scenario increase the share of renewables in all regions, with a large impact on Eastern and Western Africa, Central and South America (excluding Mexico), and Indonesia. In the African regions, the increase is dominated by solar mini-grids, while in Indonesia and Central America, hydropower use increases. For South Africa, Mexico and Southeast Asia, the effect of mitigation policies on the electricity technology chosen is small. For these regions, renewable technologies are cost-competitive even in the absence of carbon taxes.

The DLS scenario (SSP2-UA-DLS) shows that as a result of the increased level of demand, fewer locations (Figure 1-c) are served by stand-alone systems (compared to the scenarios without DLS), while there is a projected increase of diesel and hybrid PV-diesel mini-grid shares. This shift from stand-alone systems to mini-grids because of increased demand levels is a common result in previous research for SSA [3,4]. It is worth noticing that without minimum DLS levels, the average household demand projection for SSA by 2030 in the baseline scenario (480kWh/year) is lower than the average annual demand for a refrigerator. Furthermore, based on the projections of average household demand per income quintile, 33% of the global urban population and 66% of the rural population cannot afford the minimum DLS demand levels. Finally, in the combined scenario with DLS and climate policies (SSP2-2C-UA-DLS scenario), the diesel demand is reduced (compared to SSP2-UA-DLS) and compensated by increased use of PV mini-grids for most regions.

Globally and under all universal access scenarios, off-grid systems are selected as the least-cost solution for more than half of the population gaining access between 2020 and 2030 (almost 60% for UA scenarios), while the share of mini-grids and stand-alones vary by scenario. However, for India, The Republic of South Africa and the rest of South Asia, universal access is mostly achieved via densifying the current grid in all scenarios. For these regions, most of the people gaining access are located within a 50 km distance of the central grid. For many other parts of the world, mini-grids (specially sourced by PV) are the preferred option. However, note that a fixed discount rate of 10% globally was implemented for all scenarios, while some regions could have higher discount rates that could influence the least-cost technology chosen. For instance, previous research for SSA indicates that when using private discount rates depending on regional governance indexes, central grid extension might be favoured over off-grid systems for the SSA region [18].

Table 1 summarises the results obtained under all scenarios analysed in 2030 for the world (for the areas currently lacking universal access, white areas in Figure 1). The additional global annual investment for achieving universal access (SSP2-UA) by 2030 is estimated to be almost 20 billion USD on top of the baseline scenario (projected at 94 billion USD/year), and it would lead to a small (almost 4%) increase in residential $CO_2$ emissions in 2030 relative to baseline (almost 670 Mtons $CO_2$). When compared to the projected global emissions for 2030, the increase is less than 0.5%. Furthermore, achieving UA has known synergies (as documented by Nerini et al., [19]) with human development goals, such as it is fundamental for ending poverty (SDG1), supporting progress on the educational level (SDG4) and reducing inequality (SDG 10). In turn, these human-related development goals could have synergies with mitigating climate change. In the climate policy scenario, electricity-related residential CO2 emissions can be reduced by nearly 30% with a 15% additional investment on top of the SSP2-UA scenario.

Concerning the scenarios for ensuring DLS demand for all, the investment required is double the SSP2-UA scenario, and it would amount to an additional annual investment of a hundred billion USD on top of the baseline (SSP2-BL). SSA is the region with a larger increase in investment because it has the lowest projected household demand levels under the baseline demand scenario. Additionally, under this scenario, the LCOE is lower for SSA (see Appendices) due to economies of scale. Nevertheless, ensuring DLS can have larger synergies with reducing poverty (SDG1). In the combined climate policies and DLS scenario (SSP2-2C-UA-DLS), $CO_2$ emissions can also be reduced by nearly 30% with a 16% additional investment compared to the SSP2-UA-DLS. The effect of implementing a carbon tax on electrification has a similar impact on investment and emission reductions under both demand-level scenarios. However, note that there is still potential for higher emissions reduction if lower electricity demand by efficiency improvement is considered [20].

*Table 1 Data results obtained under all scenarios analysed for 2030 globally (excluding countries that achieved universal access by 2020)*

| Scenario | Description | Residential electricity demand (TWh) | Share of low carbon technologies in the electricity mix (%) | CO2 emissions from residential electricity use (Mt) | Average electricity prices ($/MWh) | Annual discounted investment required until 2030 (Billion US$/year) |
|---|---|---|---|---|---|---|
| SSP2-BL | Baseline leading to a 93% electrification rate | 1248 | 38 | 666 | 67 | 94 |
| SSP2-UA | Universal Access (UA) with baseline demand | 1340 | 36 | 691 | 81 | 113 |
| SSP2-2C-UA | UA with climate mitigation | 1340 | 53 | 492 | 93 | 131 |
| SSP2-UA-DLS | UA and ensures decent living standard levels (DLS) | 2363 | 36 | 1116 | 88 | 198 |
| SSP2-2C-UA-DLS | UA with climate mitigation and ensures DLS | 2363 | 53 | 807 | 103 | 231 |

Globally, an additional capacity of almost 60 GW on top of the baseline scenario (26 GW) is needed to achieve UA (Figure 3). Moreover, this added capacity can increase to almost 170 GW when minimum decent living standard demand levels are considered. The off-grid systems provide most of this added capacity with an estimated increase of 50GW of off-grid additional capacity for UA and almost 120GW for targeting minimum DLS (figure 3-b).

SSA, excluding the Republic of South Africa, has by far the largest share of added capacity for the electrification of new locations (figure 3-c). Furthermore, SSA has the largest variation across scenarios of need capacity (more detail is presented in Figure A3 of the supplementary material). Western Africa is the region with a larger need for capacity expansion, followed by Eastern Africa, which has the larger variation in needed capacity between the scenarios with and without the DLS consideration. For almost all regions except the Republic of South Africa, the off-grid capacity expansion increases for the DLS scenarios. For this last region, the greater demand favours the deployment of central grid extension over off-grid solutions.

## Conclusions and discussions

This study analyses least-cost optimised pathways for achieving universal electricity access globally by 2030 while considering achieving decent living standards and the synergies with climate change mitigation. For this, we look at nine electrification technologies grouped into grid extension, six mini-grid solutions and two stand-alone systems. The model integrates regional energy system data with GIS data at a higher resolution than previous global studies. This improves the assessment of best strategies for electrification based on local energy resources and population needs. It also allows an improved comparison of electrification strategies across global regions. The results discussed here can support international policymakers on the best strategies for electrification under four universal access scenarios. The result can also be compared to the business-as-usual results.

The study shows that in the absence of additional electrification policies, SDG7.1 is not achieved, and universal access may only be achieved by 2080. In this baseline scenario, more than 600 million people could still lack access by 2030, and more than 90% of them are in SSA.

Off-grid systems, i.e. mini-grids and solar home systems, are the least-cost solution for most people gaining access between 2020 and 2030. Furthermore, targeting UA leads to at least 50GW of off-grid additional capacity needed, most of which is required for SSA. When climate policies are implemented, renewables deployment is enhanced due to the higher cost of fossil sources with $CO_2$ tax. In the scenario targeting UA and minimum demand for a decent living (DLS), the additional off-grid capacity is much larger (120GW), with a preference for mini-grids over stand-alone systems. Eastern Africa has the largest increase in capacity because of its very low projected household demand under the UA baseline demand scenario.

The additional global annual investment for achieving universal access by 2030 on top of the baseline scenario (SSP2-BL) is estimated to be between 20 billion (only universal access) and almost 140 billion USD for the combined policy scenario that achieves UA with climate change mitigation and the DLS consideration (SSP2-2C-UA-DLS). Although the total investment for the DLS scenario is larger, the LCOE is lower in the SSA region, which can be helpful for people to afford the DLS demand levels. Note that beyond universal access, ensuring access to decent living is the ultimate goal, and if, due to capacity limitations, governments prioritise universal access at a lower demand level, systems should be built to accommodate capacity expansion and enable system integration. Also note that for this assessment, a fixed discount rate is implemented, enabling analysis of the deployment of central-grid versus off-grid solutions regardless of possible differences in discount rate variations across regions and between private and public investors. Therefore, a probability analysis based on different discount rates is recommended for future studies.

Even when targeting universal access, if no additional policies are considered to ensure a minimum decent living standard, an important share of the population could lack electricity access to meet these minimum levels (about 30% of global urban and 60% of global rural population). This is based on the projections of average household demand per income quintiles.

Integrating climate mitigation and UA policies would result in significant carbon emissions reduction (by 30%) with a 15% increase in investment compared to the default UA scenario. The mitigation policies analysed here focus on reducing emissions from the power production sector, but a reduction of household demand by efficiency improvement is not considered. Therefore, there is potential for larger emissions reduction. Also, it should be considered that although the increase in investment is low, it can lead to an increase in electricity prices. Hence, there is a need for complementary policies to protect people with low incomes from higher electricity prices.

# Methods

The household electrification model

A global spatial model assesses the LCOE for grid extension (following Van Ruijven's method [11]) or several off-grid options to select the least-cost option. The spatial resolution is 5'x5' with a yearly temporal resolution until 2030. Annual electrification rates for each IMAGE region are first assessed using the method of van Ruijven, and then, the access rate is calibrated using the World Bank statistics until 2020 [21]. These rates and a map with the distances to the electricity network are used to get the locations that already have access and to calculate the cost of providing access through a central network. Therefore, it is assumed that all people in a grid cell have or do not have access. The distance to the electricity network map is calculated using the available data by 2022 in OpenStreetMap [22] of the electricity network at a resolution of 30 "x30" and upscaled to the model resolution weighting with population GIS data.

For the analysis of LCOE, future electricity use per grid cell is first calculated using map projections of the urban and rural populations and regional data from IMAGE. These are average household size and electricity use for the rural and urban populations. Next, the cost of grid extension is calculated by estimating the length of transmission and distribution lines required per grid cell. It is calculated using maps of annual electricity use, expected peak demand, inhabited areas and household numbers. Additionally, technical and cost data of the high-, medium-, and low-voltage lines and transformers needed are used [11]. Then, the LCOE for the off-grid options is calculated as described in Dagnachew et al. [4]. First, the needed capacity to be installed is estimated based on the capacity factor for each technology. The capacity for wind and solar sources is calculated based on the average annual load, and it is estimated that batteries supply the extra for peak load and during night hours. The LCOE per grid cell for hydropower and the capacity factor and potential maps for solar and wind were obtained from the work of Gernaat et al. [23].

The least-cost optimisation is modelled by deciding between central grid or off-grid options. For this, a distance threshold is calculated that indicates the maximum distance at which the levelised cost of grid extension is lower than the cheapest off-grid option [4]. Furthermore, all locations within 50km of distance from the central grid are chosen for grid extension to reduce the risk for off-grid investors. For deciding between stand-alone and mini-grid options, the main criterion is the lowest cost. Additionally, for stand-alone systems, a maximum threshold on consumption density (in kWh/km2/year) is implemented [4].

IMAGE model and scenario development

IMAGE is an integrated assessment model representing different aspects of the global system, including climate, land use, energy, and economics. It is designed to explore a wide range of scenarios for the future based on different assumptions about population growth, economic development, energy use, and climate policies. It divides the world into 26 regions and has an annual resolution. However, the regions relevant to this assessment are located in Sub-Saharan Africa, Central America, South America, Asia and Oceania [24]. In this research, the focus is on its energy module, TIMER. The regional data relevant to the electrification model are $CO_2$ emissions from the power sector, electricity produced per energy source, electricity demand per household and household size. The market share of electricity-producing technologies is selected using a multi-logit function, which prioritises the cheapest technologies considering storage requirements for solar and wind sources[25]. Electricity demand for the residential sector is modelled bottom-up for the end-uses (such as light, cooling, heating and appliances) and five income quantiles for the rural and urban populations. The demand is driven by population size, floor space, appliance ownership, efficiency, and climate conditions for cooling, heating and refrigeration [26].

For analysing electrification pathways, the scenarios explored combine the shared socioeconomic pathways 2 (SSP2) with and without climate mitigation strategies, two household electricity demand levels, and two future trends in access rate. The SSP2 is the middle-of-the-road pathway with median assumptions on economic, population growth and technological progress [27]. The baseline electrification rate explored depends on projected regional socioeconomic conditions as described in van Ruijven et al. [11]. At the same time, the universal access scenario follows a linear trend for achieving the goal by 2030.

The household electricity demand levels explored are the baseline SSP2 levels and a scenario for targeting minimum decent living standard (DLS) demand in the house. It ensures that everyone has access to food refrigeration, lighting, modern cooling, one phone per household and one television/computer monitor per household [15]. The cooling demand [16] for DLS was obtained from Mastrucci et al., 2019 for rural and urban households and for five world regions. For the other appliances, average annual demand values were implemented [28].

The climate mitigation scenario implemented was obtained from the NAVIGATE project [17]. It is called the advanced production energy scenario for limiting global warming well below 2C. It is defined by propelling high technological progress for the power sector, high electrification and large implementation of wind and solar sources. A tax on CO2 emissions is implemented to favour low-carbon sources. This scenario leads to a carbon price of 337$ per ton of carbon emitted by 2030.

# Declarations

# Code availability

The code is available at https://github.com/victhaliaz/SDG7_global_electrification/

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## Figures

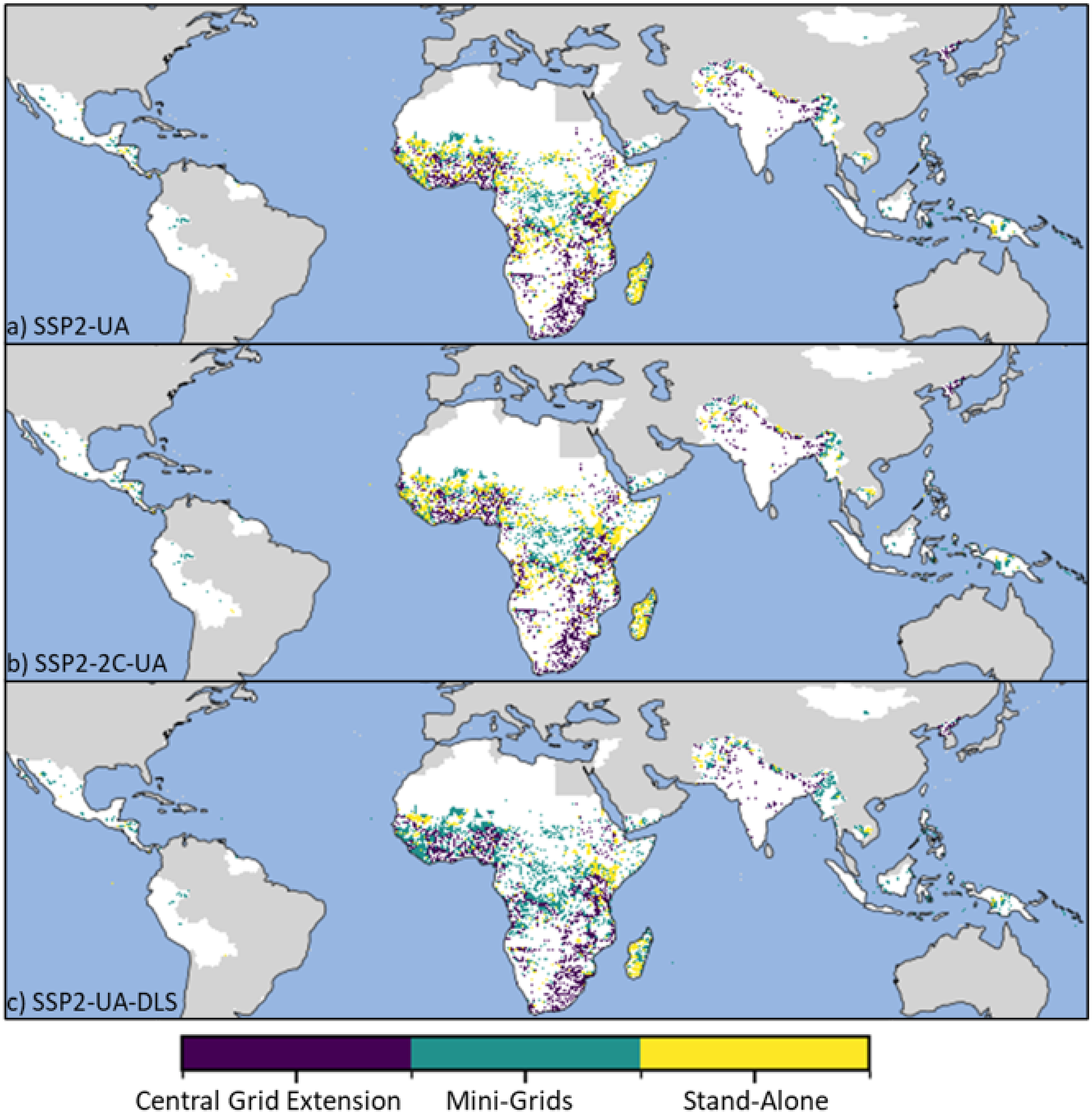
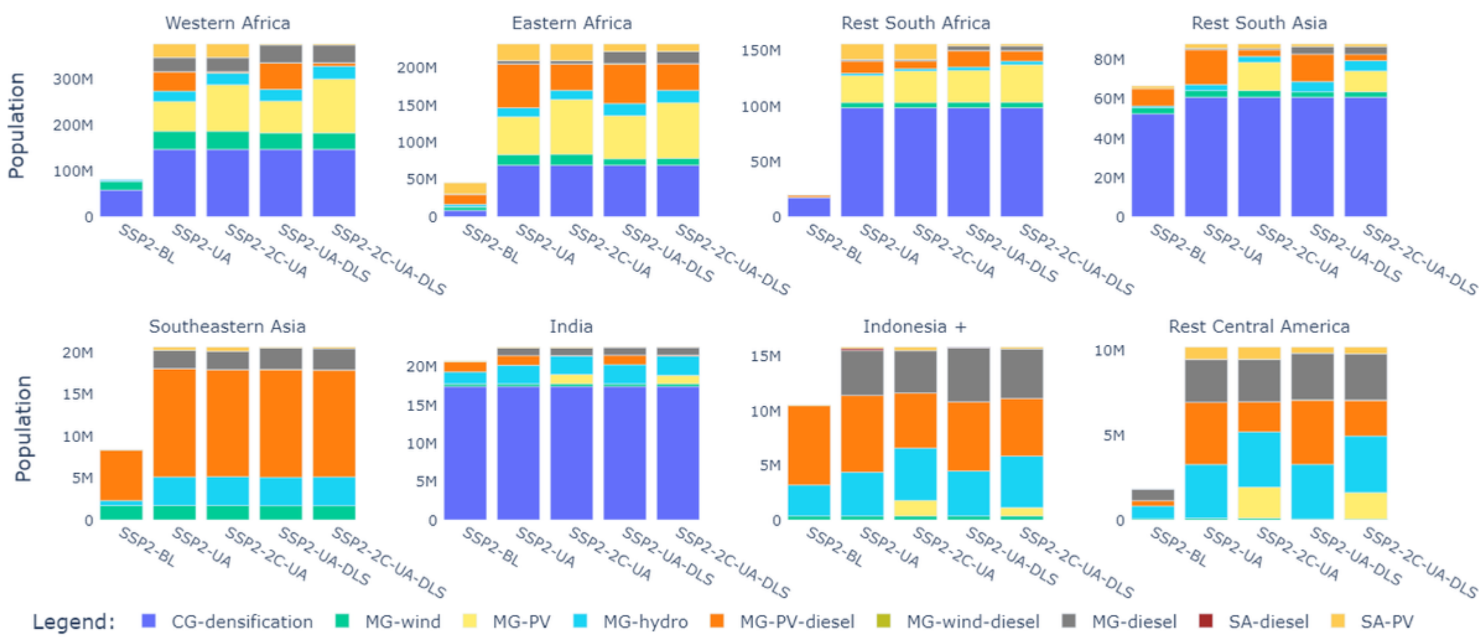


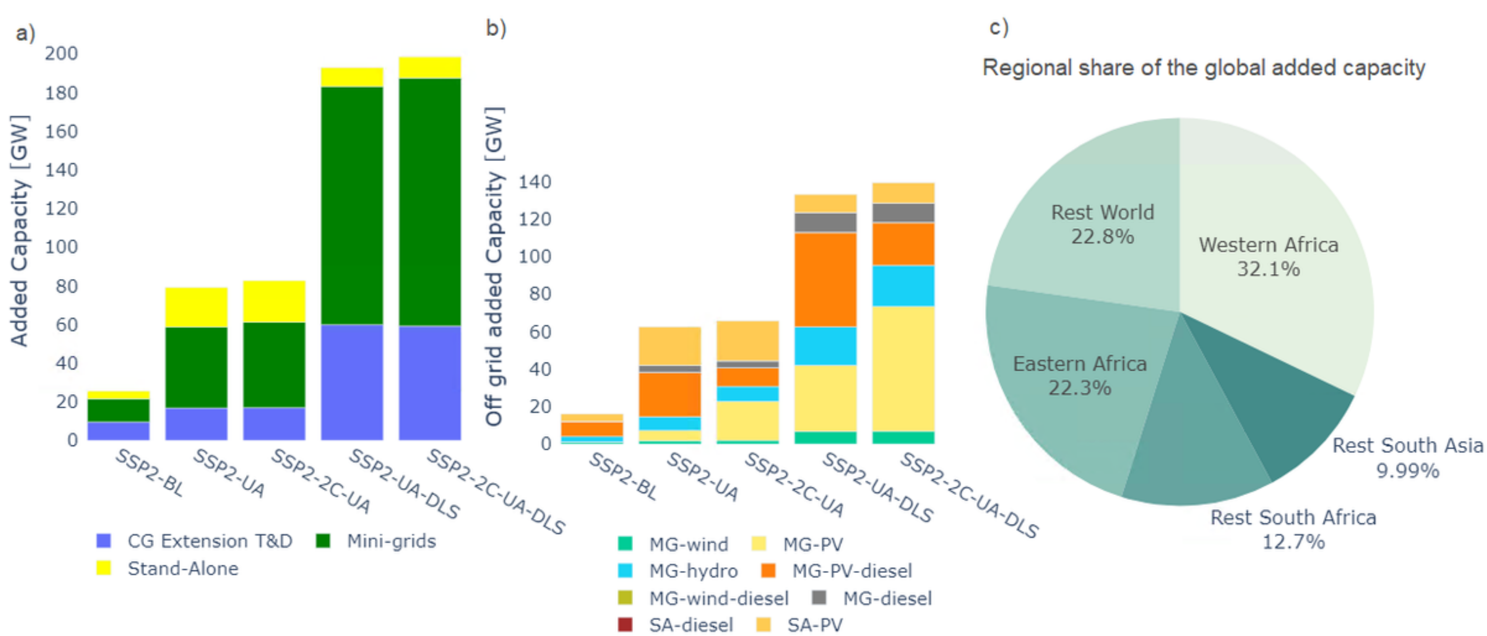

**Figure 1**

Least-cost strategies for electrification. The maps indicate cost-optimised solutions grouped into three categories: central-grid connection (purple dots), mini-grid connection (teal dots) or stand-alone systems (yellow dots) for three scenarios. a) The universal access scenario (SSP2-UA), b) the universal access with climate policies scenario (SSP2-2C-UA), c) The universal access scenario targeting minimum decent living demand levels (SSP2-UA-DLS). The grey areas represent countries that achieved universal access by 2020. The areas in white contain the countries without universal access in 2020.




## Figure 2

Distribution of the least-cost technologies selected over the population gaining access between 2021-2030 for the baseline scenario (SSP2-BL) and the four universal access scenarios. Note that the vertical axes of population size vary per region.




## Figure 3

Global additional required capacity for electrification between 2021 to 2030. From left to right, plot a) shows the added capacity for electrification for central grid (CG) extension and the off-grid solutions. b) Indicates the added capacity from the different off-grid technologies considered; “MG” means mini-grids, and “SA” means Stand-alone systems. c) Shows the regional share of added capacity for electrification (under the DLS scenario)-for locations that lacked access by 2020.

# Supplementary Files

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- VZAppendices.docx