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Model-based scenarios for rural electrification in developing countries

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ABSTRACT

Promoting access to modern energy forms in developing countries to replace traditional fuels is high on the political agenda. This paper describes the development and application of a global model for rural electrification. The model is used to assess future trends in electrification, and the associated investment needs. The model is applied for a set of electrification scenarios. We find that the trend in increasing electrification differs considerably among world regions: in Latin America and Asia access to electricity takes place at lower income levels than in Africa. Under business-as-usual developments, universal access to electricity is not reached by 2030 in Latin America, Asia or sub-Saharan Africa. Investments per household depend strongly on population density, implying relatively low costs in most Asian subregions. Global cumulative investments to reach universal access to electricity by 2030 amount 477–868 billion USD_{2005}, which would be 238–400 billion additional to business-as-usual (or 12–20 billion USD_{2005} per year). The potential for mini-grid and off-grid technologies is expected to be high in Latin America and sub-Saharan Africa, and lower in Asia. This is a result of high costs of grid electrification at low population densities in large parts of rural Africa and Latin America.

1. Introduction

Promoting access to modern energy forms in developing countries to replace traditional fuels is high on the political agenda [1,2]. Modern energy forms are more efficient and cleaner, they facilitate better living conditions and higher productivity. Such modern energy forms include electricity, LPG and natural gas. It has been shown that access to modern energy forms brings benefits to human wellbeing and economic development. Although there is no specific Millennium Development Goal (MDG) on modern energy use, access to energy is in fact required to reach most of the MDGs that have been formulated [3]. In that context, it should be noted that currently, 1.6 billion people in developing countries have no access to electricity and an estimated 2.4 billion people rely on wood or charcoal for cooking and water heating [1,3,4].

Energy use, economic development and environmental pressure are closely interlinked [2,5,6]. The future development of the global energy system and the resulting environmental pressure has been analysed in numerous studies [5,7,8]. However, limited attention has been paid to the transition from traditional to modern energy forms and the associated investments. In general, global energy models and integrated assessment models hardly include the dynamics of developing countries explicitly [9–11].

In this paper, we present a global model for access of households to electricity. The presented model is part of the global integrated assessment model IMAGE [12] and used within the global energy system simulation model TIMER [13,14]. Access to electricity also drives household electricity demand through ownership and use of appliances [15–17]. With this model, we analyse how the access to electricity may develop over the next decades and what extra policies are needed to ensure access to electricity for all households. The paper also analyses the required investments for increasing electrification and the cost-effective potential for off-grid technologies.

The model is developed for global application in the context of a global energy model. However, the dynamics of electrification are most interesting and relevant for regions with low access to electricity. Therefore, we will focus on the world regions Latin America, Asia (excluding China, Japan and Korea) and Sub-Saharan Africa (see Table 1 for definitions).

This paper is organised as follows. First, Section 2 presents a literature review on the benefits of access to electricity and the determinants of electrification rates. Next, in Section 3 we present

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Table 1
Definition of geographic regions used for reporting in this paper and the underlying model. Details of the regional definition can be found at www.pbl.nl/IMAGE.

World region	Aggregated region	Model regions
Latin America (LAM)	Brazil	Brazil
	Mexico	Mexico
	O-LAM	Other Central America
		Other South America
Asia	India	India
	Indonesia	Indonesia
	O-ASIA	Other South Asia
		Other South-East Asia
Sub-Saharan Africa (SSA)	South Africa	South Africa
	O-SSA	Eastern Africa
		Western Africa
		Other Southern Africa

the electrification model and the assumptions of the scenario analysis. In Section 4, we present the results of the analysis. Finally, Section 5 discusses the findings of the paper.

2. Literature review on the benefits and determinants of rural electrification

2.1. Benefits of rural electrification

Many benefits from electrification are expected by people and policy makers. We have performed a literature study to assess scientific evidence on electrification benefits. The potential benefits can be categorized at the different levels to which an electricity network can be expanded and at which access to electricity can have benefits: (1) village or community centres, to supply public services; (2) enterprises in the village/community centre or main enterprises and farms in the surroundings and (3) all individual households. We briefly discuss the benefits at these different levels.

2.1.1. Benefits of access at the community level

At the community level, access to electricity can have benefits for education, health and water supply. It is found that access to electricity makes it more attractive for educated staff to live in rural areas, increasing the quality of schools and hospitals [18,19]. Access to electricity could also improve access to drinking water by the use of water pumps. This is very important as studies indicate that in developing countries getting water may typically take 1–3 h in rural areas [20,21]. Street lighting, which increases safety, is also a benefit of electricity access at the community level.

2.1.2. Benefits of access at the enterprise level

Access to electricity increases options for enterprises to mechanise production processes and enhance computerisation and communication [3]. In general, a correlation between investments in electricity infrastructure for rural regions and GDP-growth has been observed [22]. This is also related to indirect factors, such as communication technology that depend on the presence of electricity. At the same time, it should be noted that other factors, such as a social network or access to markets and road access can be more relevant for rural entrepreneurs [23].

2.1.3. Benefits of access at the household level

For households, access to electricity leads to improved lighting and access to television [24]. This is shown to have positive impact on indoor air quality, education and hygiene [25,26]. Other benefits that are also often referred to are a reduction in firewood consumption and reduced time use for household tasks, but very little evidence for this can be found in the scientific literature. Studies have shown that even when people can afford electric cook stoves, rural households in India and Africa generally prefer cooking on wood or other fuels [27]. For household tasks it is important to realise that most inhabitants of rural areas in developing countries cannot afford more appliances than electric lighting, TV and an iron. Therefore, time use for collecting firewood and household tasks remains high, even with access to electricity [22].

An issue that is important across all three levels of access is the quality of electricity supply. It is essential for health clinics and enterprises, but also households require reliable power supply before people start using electricity for vital functions like cooking. Most literature on this issue, deals with the influence of outages on firms. The costs of outages for enterprises are found to be significant in developing countries [23,28,29], and many firms find it attractive to maintain their own generation capacity [30].

2.2. Determinants of the rural electrification rates

The literature indicates that access to electricity is a diverse issue. For instance, some countries have high access to electricity at relatively low income levels (Mongolia, China and Yemen), whereas other countries still have low electrification at relatively high income levels (Namibia, Gabon or Botswana). What drives these differences in the level of access to electricity? Many rural electrification projects have been carried out, and are evaluated in literature. These evaluations show that similar policies can lead to different results under different conditions, and that external factors play an important role in the success of electrification projects.

According to Zomers [31], the main explanations for the success of electrification programmes are long-term governmental commitment and utilities with sufficient autonomy to prevent political interference. Also, proper tariff setting helps to support rural services, but preferably a utility should be financially robust based in non-rural electricity supply. Large scale programmes can achieve economies of scale and parallel development programmes can help to maximize the use of electrification. Finally, employment of local workers is important, but the staff should also be properly trained. Another important factor for the success of rural electrification is a large reserve capacity in electric power generation [32]. For the financial operation of utilities it is not only important that tariff setting functions properly, but also that billing and bill collection are organised well, and that line losses are not extremely high [33–35].

Also the actor that is allowed to make decisions plays a role. Literature shows that utilities have their own financial responsibility for rural electrification programs, and hence, they play a role in ambition setting and achievement [31,36,37]. In the best case, the decisions about where to engage in electrification are based on standards or criteria. Such criteria support electrification in places where it is cheapest. These are projects where the infrastructure investments are low compared to the potential demand for energy. In practice, this applies to communities that are closest to the existing grid, have a high population density, or have high economic activity. Social criteria have also been found in project evaluations (such as preferring the poorest areas over others) [36], but are less common as they undermine the financial position of utilities and governments.

In many countries, households have to pay a connection fee, and have to make their own decision about whether or not to have access to electricity in their homes. This decision is generally based on financial factors, such as the height of the connection fee, or whether there is a possibility to spread payments over time [31,36,38].

3. Methodology of modelling rural electrification

The model used in this paper is based on two main steps. The first step determines the electrification rate on the basis of econometric analysis. The second step determines the costs of electrification on the basis a simple power grid design, taking into account the costs of different components of the grid, but also the local electricity demand (based on population density).

3.1. Level of electrification

The discussion above shows that several variables influence the level of electrification. We compiled a dataset to analyse the influence of these variables on access to electricity. It includes for instance economic activity, (rural) population density, effective governance, urbanization level and industrial activity (see Table 2 for a complete overview of the indicators, definitions and sources). We analyzed the influence of these factors at the country level in a multivariate linear regression analysis to develop an econometric trend model for national electrification levels [39].

First, the national electrification level (E_N) was log-transformed, to be able to perform linear regression and remain within a zero to 100% range:

$$E_{\text{National}}^{\text{Transformed}} = \ln\left(\frac{E_N}{1-E_N}\right)(-) \quad (1)$$

Second, a series of linear coefficients ($\beta_1, \ldots, \beta_N$) for the different drivers of electrification ($X_1, \ldots, X_N$) was sought in a stepwise, multivariate linear regression analysis:

$$E_{\text{National}}^{\text{Transformed}} = \alpha_0 + \beta_1 X_1 + \cdots + \beta_N X_N(-) \quad (2)$$

The results of this analysis are shown in Table 3. We tested for eight different models, aggregated in two sets of analyses. The first set (models 1, 1a, 1b and 1c) includes regression on all available variables. It shows that, for the global dataset (model 1), electrification is significantly related to GDP, population density, urbanisation and secondary school enrolment. For the individual world regions, however, results are very different. For Latin America, GDP per capita is the only significant variable (model 1b), whereas for Sub-Saharan Africa (model 1a) the list of explanatory variables includes among others urbanization, effective governance, public sector consumption and population density. For the Asian region, the average World Governance Indicator index is most significant (model 1c).

The second set of analyses included only variables that can be forward-projected in the context of a global integrated assessment model and focused on using a consistent set of similar variables across regions (models 2, 2a, 2b and 2c). For this, we first excluded secondary school enrolment from the global analysis, which led to a model that includes GDP per capita, rural population density and urbanization (model 2). Next, we ran regional regressions using only these three variables to explain national electrification levels. The results of this analysis show (among others) a much stronger coefficient for GDP per capita in Asia and Latin America than for Sub-saharan Africa. This indicates that electrification generally requires higher income levels in Africa than in the other regions.

To avoid that long-term forward projections for specific regions are dominated by low-electrified countries in the dataset, we assumed in forward calculations that the regional models converge linearly to the global model between GDP levels of 5.000 and 30.000 int$_{2005}$/capita/yr.

Based on rural electrification data from literature a relation between rural (E_R) and national electrification levels could be established:

$$E_R = \varphi E_N^2 + \mu E_N + \gamma \ (\%) \quad (3)$$

in which $\varphi = 0.9675$, $\mu = 0.0183$ and $\gamma = 0.004$ lead to an R^2 value of 0.99. Urban electrification levels can be directly derived from the national and rural electrification levels and urbanization rates.

The results of the model, compared to historic data [40,41] are shown in Table 4. If the national and/or rural electrification level calculated with the trend model deviates from historic data in 2005, a correction factor has been applied. In future projections, this correction factor is assumed to converge linearly to zero in 2100.

3.2. Investment model

As a next step, a relatively simple, generic model for network design was developed, to determine the investment need for rural electrification on the level of 0.5 × 0.5 degrees grid cells. This model assumes that a grid cell is either fully electrified, or has no rural access to electricity. The order in which grid cells are electrified

Table 2
Variables and data-sources used in multivariate statistical analysis of rural electrification.

Variable	Abbreviation	Definition	Source
Electrification level	E	% of population	[40]
GDP per capita, ppp	GDPpc	$2005	[52]
Population density	PD	Persons/km^2	[52]
Rural population density	RPD	Rural persons/km^2	[53]
Urbanisation	Urb	% of Population	
Share of Industry in GDP	IVA	% of GDP	[52]
Share of services in GDP	SVA	% of GDP	[52]
Public sector consumption relative to GDP	PSC	% of GDP	[52]
Exports of goods and services	Exp	% of GDP	[52]
External balance in goods and services	ExtB	% of GDP	[52]
Fuel exports (% of merchandise exports)	FExp	% of merchandise exports	[52]
Secondary school enrolment	SSE	% of age group	[52]
Foreign Direct Investment	FDI	% of GDP	[52]
Effective governance	EffGov	Index score	[54]
World governance indicator average	WGI	Average of indices on: • Voice and accountability • Political stability and absence of violence • Government effectiveness • Regulatory quality • Rule of law • Control of corruption	[54]

Table 3
Parameterisation of electrification trend model base on regression to data from IEA [41] and Legros et al. [40].

1	Model 1		Model 1a		Model 1b		Model 1c		Model 2		Model 2a		Model 2b		Model 2c	
Region	World		SSA		LAM		ASIA		World		SSA		LAM		ASIA	
Variables	All		All		All		All		All except SSE		LN(GDP), LN(RPD), Urb		LN(GDP), LN(RPD), Urb		LN(GDP), LN(RPD), Urb	
Countries	79		26		18		10		79		26		18		10	
R^2	0.878		0.937		0.700		0.956		0.816		0.637		0.720		0.783	
Variables	β	*p*-Value	β	*p*-Value	β	*p*-Value	β	*p*-Value	β	*p*-Value	β	*p*-Value	β	*p*-Value	β	*p*-Value
Constant	−8.694	0.000	−3.642	0.000	−12.652	0.000	−1.609	0.308	−12.600	0.000	−10.461	0.000	−10.697	0.005	−18.625	0.026
GDPpc	–	0.326	–	0.593	–	0.506	–	0.538	–	0.197	–	–	–	–	–	–
LN(GDPpc)	0.567	0.004	–	0.710	1.693	0.000	–	0.638	1.231	0.000	0.843	0.002	1.338	0.019	2.197	0.014
$GDPpc^2$	–	0.406	−1.372E−08	0.000	–	0.489	–	0.529	–	0.198	–	–	–	–	–	–
PD	−0.020	0.024	–	0.665	–	0.660	–	0.259	–	0.301	–	–	–	–	–	–
LN(PD)	–	0.377	–	0.828	–	0.592	–	0.277	–	0.363	–	–	–	–	–	–
PD^2	–	0.155	1.326E−05	0.000	–	0.647	–	0.297	–	0.450	–	–	–	–	–	–
RPD	–	0.354	–	0.378	–	0.659	–	0.259	–	0.671	–	–	–	–	–	–
LN(RPD)	0.510	0.000	–	0.780	–	0.429	–	0.298	0.467	0.000	0.632	0.000	0.004	0.986	0.404	0.449
RPD^2	–	0.340	–	0.068	–	0.792	–	0.292	–	0.569	–	–	–	–	–	–
Urb	0.039	0.000	0.058	0.000	–	0.318	–	0.670	0.044	0.000	0.037	0.025	0.018	0.558	0.009	0.762
IVA	–	0.573	–	0.561	–	0.883	–	0.820	–	0.684	–	–	–	–	–	–
SVA	–	0.890	–	0.527	–	0.675	0.086	0.029	–	0.150	–	–	–	–	–	–
PSC	–	0.508	0.024	0.004	–	0.670	–	0.561	–	0.308	–	–	–	–	–	–
Exp	–	0.279	–	0.707	–	0.633	–	0.695	–	0.727	–	–	–	–	–	–
ExtB	–	0.970	–	0.632	–	0.979	–	0.487	–	0.361	–	–	–	–	–	–
FExp	–	0.416	–	0.979	–	0.608	0.089	0.030	–	0.261	–	–	–	–	–	–
SSE	0.039	0.000	0.028	0.002	–	0.364	–	0.149	–	–	–	–	–	–	–	–
FDI	–	0.408	–	0.451	–	0.663	–	0.514	–	0.439	–	–	–	–	–	–
EffGov	–	0.581	0.441	0.019	–	0.689	–	0.780	–	0.553	–	–	–	–	–	–
WGI	–	0.765	–	0.890	–	0.335	3.907	0.000	–	0.570	–	–	–	–	–	–

Table 4
Model performance compared to national and rural electrification levels for 2005.

	Data $E_{national}$	Predicted $E_{national}$	Data E_{rural}	Predicted E_{rural}
Brazil	100%	95%	88%	95%
O-LAM	88%	94%	63%	77%
India	66%	67%	53%	42%
Indonesia	61%	75%	31%	40%
O-ASIA	61%	66%	50%	38%
South Africa	78%	77%	55%	56%
O-SSA	25%	22%	11%	7%

over time within a world region is based on the levelised cost for transmission and distribution (T&D) of electricity. Because the grid cells are defined in terms of degrees, their actual size varies around the globe (small at the poles, and larger towards the equator). The basic available information per grid cell is its area, and by assuming that grid cells are square, the square root can be used to derive its length and width.

The model is based on a simple tree-like structure (Fig. 1) to determine the length of power lines in a grid cell (based on [33,42]). Below we briefly describe the main assumptions made in the model. It should be noted that for some assumptions considerable uncertainties exist. In the section on scenarios (Section 3.3) we describe how the uncertainty ranges have been used in the actual model calculations.

The main input variables, assumptions and relations of basic variables are shown in Table 5. As Fig. 1 indicates, the Medium Voltage (MV) level has a key position in the network design. It determines the need for low-voltage networks and high-voltage capacity, depending on variability in grid cell area, population density and peak demand of households. At the MV level, we assume that Single Wire Earth Return (SWER) wires are used. This line type has relatively high line losses, which are counterbalanced by its low investment costs. These lines are commonly used for rural electrification in Australia [43] and Tunisia [3].

First, the amount of SWER lines required per grid cell is derived from the maximum capacity of 50 kW per line, and the required capacity of the network, given by the number of households and their assumed peak demand:

$$\text{SWER lines} = \frac{\text{HH}_{\text{rural}} \times \text{Peak}_{\text{HH}}}{\text{Capacity}_{\text{SWER}}} (\text{lines}) \tag{4}$$

From this, we first derive the demand for low-voltage networks. Low voltage networks are assumed to be square areas, with a network structure as shown in the left graph of Fig. 1. The LV networks are limited by either their maximum capacity (in case of high population density) or the maximum line-length (in case of low population density). The required number of low voltage networks in a grid cell is therefore either determined by the capacity of lines, or the maximum area that can be reached with a low-voltage network.

The minimum number of LV networks per SWER line, as limited by capacity is given by:

$$\text{NrLVs}_{\text{capacity}} = \frac{\text{HH}_{\text{rural}} \times \text{Peak}_{\text{HH}}}{\text{Capacity}_{\text{LV}}} (\text{LV networks}) \tag{5}$$

$$\min \text{LV}_{\text{capacity}} = \frac{\text{NrLVs}_{\text{capacity}}}{\text{SWER lines}} (\text{LV networks}) \tag{6}$$

The minimal number of LV networks per SWER line that is required on the basis of maximum line length is defined as:

$$\min \text{LV}_{\text{line length}} = \frac{\left(\frac{\text{Inhabited Area}_{\text{rural}}}{\text{SWER lines}}\right)}{\max \text{Area}_{\text{LV network}}} (\text{LV networks}) \tag{7}$$

Than, the actual number of LV networks per SWER line is the maximum of the required LV networks on the basis of capacity or line length, but maximised at the number of rural household in the grid cell:

$$\text{LVs}_{\text{SWER}} = \min\left\{\text{HH}_{\text{rural}}, \max\left\{\min \text{LV}_{\text{linelength}}, \min \text{LV}_{\text{capacity}}\right\}\right\} \times (\text{LV networks}) \tag{8}$$

Now, the actual number of households per LV network is given by the total rural households and the number of LV networks:

$$\text{HH}_{\text{LV}} = \frac{\text{HH}_{\text{rural}}}{\text{LVs}_{\text{SWER}} \times \text{SWER lines}} (\text{HH/network}) \tag{9}$$

From this, we can calculate the unit line length for LV network, u (see the left graph of Fig. 1 for the meaning of u in the optimal network design of Sebitosi et al. [33]):

$$u = \sqrt{\frac{\text{InhabitedArea}_{\text{rural}}}{\text{HH}_{\text{rural}}}} \times \frac{\sqrt{2}}{2} \quad (\text{km}) \tag{10}$$

This enables us to calculate the total LV line length per LV network, based on assumptions of Sebitosi et al:

$$\text{LV length}_{\text{LV}} = 1.333 \times \text{HH}_{\text{LV}} \times u\ (\text{km}) \tag{11}$$

And finally, we determine the total LV line length for the grid cell by:

$$\text{LV length} = \text{LV length}_{\text{LV}} \times \text{LVs}_{\text{SWER}} \times \text{SWER lines}\ (\text{km}) \tag{12}$$

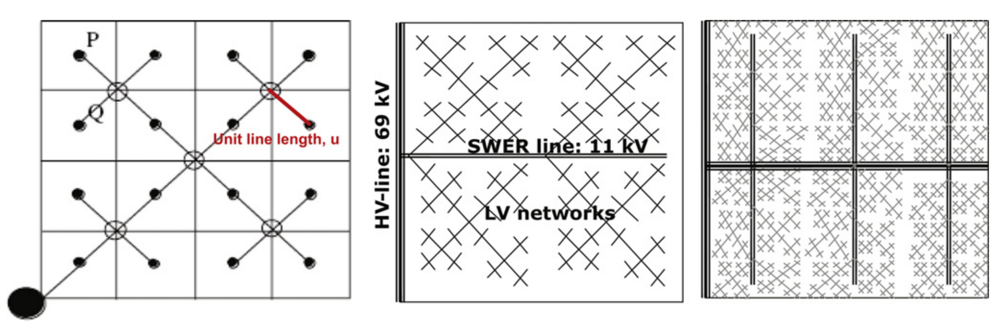

Fig. 1. Left graph: least line length network design for a distribution network (used in this model for low voltage networks) [33]. Right graphs: generic electricity network design for T&D costs model at 0.5 × 0.5 degree grid cell level, containing high, medium and low-voltage networks. Examples for grid cells with low (middle graph) and high (right graph) population density.

Table 5
Input variables, description and assumptions for electricity grid investment model (all units are per grid cell of 0.5x0.5 degree).

Variable Name	Description	Unit / formula
$PopDens_{rural}$	Rural population density	person/km^2
Area	Area of a grid cell	km^2
$Persons_{HH}$	Persons per household (HH)	Persons
HH_{Rural}	Number of rural households	$Area \times PopDens_{rural}/Persons_{HH}$
$Demand_{HH}$	Annual electricity demand per HH	kWh
$Peak_{HH}$	Peak electricity load per HH	W
$Share_{residential}$	Share of residential electricity demand in total electricity use	%
$Capacity_{SWER}$	Maximum capacity of a SWER line	50 kW
$Capacity_{LV}$	Maximum capacity of an LV line	10 kW
$MaxLength_{SWER}$	Maximum length of a SWER line	50 km
$MaxLength_{LV}$	Maximum length of an LV line	30 km
$Cost_{HV}$	Investment cost per km HV line	USD_{2005}
$Cost_{MV\_SWER}$	Investment cost per km MV SWER line	USD_{2005}
$Cost_{LV}$	Investment cost per km LV line	USD_{2005}
$Cost_{transformer}$	Investment cost per transformer	USD_{2005}
$Cost_{connection}$	Investment costs for metering & wiring per household	USD_{2005}
GCsperHV	No. of grid cells sharing one HV line	2
R	Discount rate	10%
Lifetime	Economic lifetime of infrastructure	20 year
Annuity	Annuity factor for investment costs	$R/1-(1+R)^{Lifetime}$
$O\&M$	Annual O&M cost	3% of investment
$MaxArea_{LV}$	Maximum area covered by a LV line (due to maximum line length)	$(\text{Length LV}/\sqrt{2})^2 = 450\ \text{km}^2$
MaxHHsLV	Maximum number of HHs per LV network (due to maximum capacity)	$Capacity_{LV}/Peak_{HH}$
F	Disaggregation factor, represents clustering of settlements. Value of zero for clustered settlements, 1 for fully scattered distribution.	Constant value of 0.5 globally assumed. See [3] for detailed definition.
$InhabitedArea_{rural}$	Area within grid cell that is considered inhabited	$Area \times F$

For the medium voltage network, the actual reach (or length) of a SWER line is approximated by assuming that the grid cell is square shaped and each Low Voltage (LV) network covers a square shaped area as well (see Fig. 1, middle and right graphs). Then, the actual length of a SWER line is given by:

$$\text{Reach}_{SWER} = \frac{\text{Inhabited Area}_{rural}/\text{SWER lines}}{2\sqrt{\text{Area}_{LV}}}\ (\text{km}) \tag{13}$$

Limited by the maximum line length of a SWER line, the total kilometres of MV SWER line for a grid cell is given by:

$$\text{SWER length} = \min\{\text{Reach}_{SWER}, \text{maxLength}_{SWER}\} \times \text{SWER lines}\ (\text{km}) \tag{14}$$

Finally, it is assumed the each two grid cells share a high voltage (HV) line. However, in case of densely populated cells, the capacity of SWER lines can be too limited to cover the entire grid cell. This would require extra lines to reach the parts deeper into the grid cell (see the right graph to the right in Fig. 1). For simplicity, it is assumed this will be an HV line, which crosses the entire grid cell width. It is calculated by assuming the inhabited area of a grid cell to be square shaped. The number of additional HV lines needed is determined by calculating how many HV&SWER combinations would cover the entire inhabited area, with:

$$\text{Additional HV lines} = \max\left\{0, \frac{\sqrt{\text{Inhabited Area}_{rural}}}{2 \times \min\{\text{Reach}_{SWER}, \max \text{Length}_{SWER}\}} - 1\right\} (\text{lines}) \tag{15}$$

The division is rounded to an integer, and reduced with 1, to avoid overestimating at low population densities due to rounding. The total HV length for a grid cell is given by:

$$\text{HV length} = \frac{\sqrt{\text{Area}}}{2}\text{Additional HV lines} \times \sqrt{\text{Inhabited Area}_{rural}}\ (\text{km}) \tag{16}$$

The number of transformers is assumed to be equal to the number of points where one line of a lower voltage splits off from a higher voltage network. This is equal to the number of additional HV networks, plus the SWER lines in a grid cell and the number of low-voltage networks in a grid cell:

$$\text{Transformers} = \text{SWER lines} + (\text{LVs}_{SWER} \times \text{SWER lines}) + \text{Additional HV lines}\ (\text{nr. transformers}) \tag{17}$$

Finally, we assume that the LV network goes up to the households dwelling. For connection some additional costs need to be made. These are either for a meter and internal wiring or for the use of “compact ready boards”. The latter in general consists of a box with an outgoing electric wire for a light bulb and one or more power points for small appliances.

The investments per connection are calculated by combining the line lengths of different voltage levels and the number of other cost components (transformers and metering & wiring) with the investment costs per unit of kilometre. The following formulas apply at the grid cell level to determine investments in HV, MV, LV networks, transformers and household connections:

$$\text{Inv}_{HV_{gc}} = \text{HV length} \times \text{Cost}_{HV}\ (\$) \tag{18}$$

$$\text{Inv}_{MV_{gc}} = \text{SWER length} \times \text{Cost}_{MV\_SWER}\ (\$) \tag{19}$$

$$\text{Inv}_{LV_{gc}} = \text{LV length} \times \text{Cost}_{LV}\ (\$) \tag{20}$$

$$\text{Inv}_{\text{Transformer gc}} = \text{Transformers} \times \text{Cost}_{transformer}\ (\$) \tag{21}$$

$$\text{Inv}_{\text{Connection gc}} = \text{HHs}_{rural} \times \text{Cost}_{connection}\ (\$) \tag{22}$$

The investment costs assumptions are shown in Table 6. These cost components can be added together into the total investments,

Table 6
Assumptions on cost components of rural electricity networks.

Variable	Low inv. costs	High inv. costs	Source
High voltage line	28,000 USD/km	78,000 USD/km	[55]
Medium voltage line	5000 USD/km	9000 USD/km	[43]
Low voltage line	3500 USD/km	5000 USD/km	[55]
Transformers	5000 USD/unit	5000 USD/unit	
Connection costs	100 USD/hh	250 USD/hh	[56]

which can be expressed in terms of investment per household and as the levelised costs per kWh:

$$\mathrm{Inv}_{\mathrm{Total}} = \mathrm{Inv}_{\mathrm{HV}} + \mathrm{Inv}_{\mathrm{MV}} + \mathrm{Inv}_{\mathrm{LV}} + \mathrm{Inv}_{\mathrm{Transformer}} + \mathrm{Inv}_{\mathrm{Connection}}\ (\$) \tag{23}$$

$$\text{Inv Per Connection} = \frac{\mathrm{Inv}_{\mathrm{Total}}}{\mathrm{HHs}_{\mathrm{Rural}}}\ (\$/\mathrm{HH}) \tag{24}$$

Finally, to determine the levelised network costs, we divide the annuitized investments by the electricity demand by households:

$$\mathrm{TD}_{\mathrm{levelised}} = \frac{\mathrm{Inv}_{\mathrm{Total}} \times \mathrm{Annuity} + \mathrm{O\&M} \times \mathrm{Inv}_{\mathrm{Total}}}{\mathrm{Demand}_{\mathrm{HH}}}\ (\$/\mathrm{kWh}) \tag{25}$$

It should be noted that the model only describes the costs of new electrification of rural areas in developing countries and not of, e.g., capacity increase of existing grids. In general, electricity demand in those areas is limited to lighting and entertainment. Based on assumptions elaborated in Modi et al. [3], we distinguish two extreme cases of residential energy demand:

- *Low demand:* one traditional light bulb (40 W), and one out of three households a TV (60 W), that is 60 W; assumed for 3 h a day this is ~65 kWh/HH per year.
- *High demand:* the consumption of 115 W (television, light, refrigerator) for 10 hours per day: 420 kWh/HH per year.

The investment model determines the costs of an entire T&D network in an area. However, other sectors like agriculture, public services and small businesses will also use electricity. Studies expect that that non-residential electricity demand will be low [3]. The share of residential electricity demand in rural electricity consumption is therefore assumed to be 90% for the low demand scenario and 75% for the high demand scenario. In the calculations, we also take the numbers on household electricity demand as described above as constant. These demand assumptions only provide enough capacity for some lighting and small appliances. If households start owning heavier appliances and air conditioners, the network should probably be reinforced, as demand goes up. However, we assume that this trend would not be part of policies that aim to provide access to electricity to rural households, but would come from normal network decisions on operation and expansion (once the initial access has been made).

3.3. Scenarios for rural electrification and investment

We use this model to calculate different scenarios for rural electrification. The uncertainties discussed in the previous section can be grouped into two main categories: (1) the investment costs and (2) the electricity demand. We combine optimistic and pessimistic values for each of these categories to develop four different scenarios as indicated in Fig. 2.

We used the scenario developed for the OECD Environmental Outlook [44] on population, urbanisation and GDP (Table 7) to derive the trend in rural electrification and the required investments for a universal access scenario. The values for these parameters in 2005 and 2030, for the regions analysed in this paper are indicated in Table 6. We interpret universal access as 95% of the rural population being connected to the power grid. The reason is that for the remaining 5%, investment costs tend to become extremely high, and off-grid options are mostly more attractive.

4. Results

4.1. Projections for electrification levels

Fig. 3 shows the electrification levels for different world regions as calculated using the model presented in Section 3. In Latin America, rural electrification levels are already relatively high, with almost 90% in Brazil and 63% in Other Latin America in the year 2005. Under business as usual projections, access in Other Latin America is projected to increase to almost 80% in 2030. In Asia,

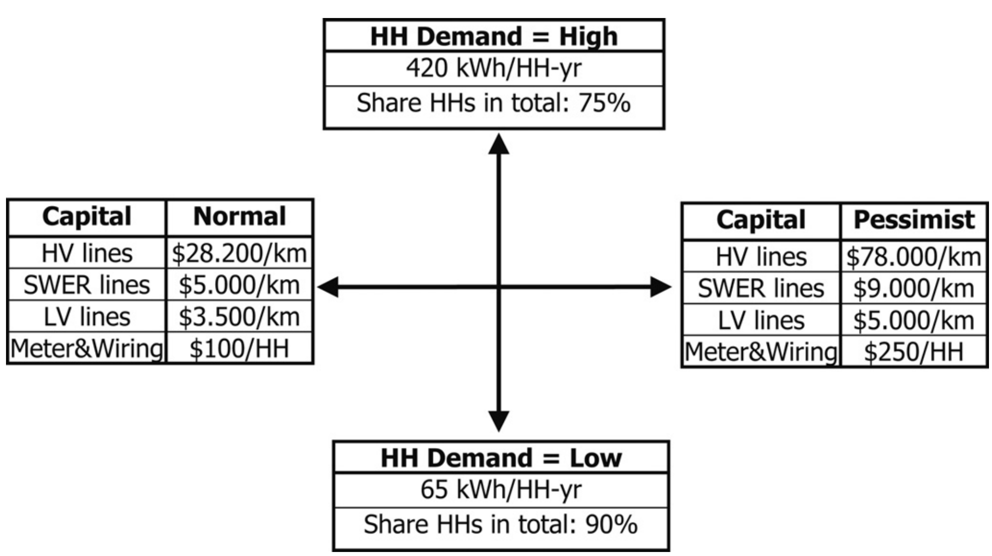

Fig. 2. Input variables for the four scenarios.

Table 7
Key assumptions for population, urbanisation and economic development in the baseline scenario for the OECD environmental outlook [44].

	Population (million)		Urbanisation		GDPpc, ppp ($\$_{2005}$)	
	2005	2030	2005	2030	2005	2030
Brazil	186	217	84%	91%	8505	18456
O-LAM	265	346	73%	81%	8240	16236
India	1131	1485	29%	41%	2154	8770
Indonesia	225	279	47%	67%	3176	8643
O-ASIA	726	1019	34%	49%	2879	6447
South Africa	48	55	59%	71%	8295	18281
O-SSA	716	1248	34%	47%	1285	2754

about 40% of rural households had access to electricity in 2005. Also here, the projected increase under business as usual is very significant to almost full access in India and Other Asia, and more than 60% in Indonesia. Sub-Saharan Africa shows wide divergence in rural electrification levels: in 2005 access in the Republic of South Africa was over 50%, but rural access in the rest of Sub-Saharan Africa was only 11%. Following the business as usual trend, this would increase to 82% in 2030 for the Republic of South Africa, but only to 30% for Other Sub-Saharan Africa.

In other words, the gap between the projected level of access and universal access in 2030 is largest in Sub-Saharan Africa. In contrast, much less additional effort would be needed in Latin America and Asia.

4.2. Investments for grid electrification

The required investments for increasing electrification levels depend largely on the assumptions on investment cost for grid equipment, but also on population density. Fig. 4 shows the investment cost (showing different components) for the four different scenarios for India laid out in Section 3. We have sorted the investment costs and plotted against the cumulative share of rural population. Generally, the left end of the curves contains grid-cells with high rural population density, and the right end of the curve includes grid-cells with low rural population density. It shows that the total investment costs and structure of investments is more determined by uncertainty in the investment costs, than by the different levels of peak demand. Low-voltage (LV) lines account for a large share of the investments, as they can constitute long distances in less populated areas. Uncertainties that influence the results seem to be the costs for metering and wiring (in house) and the role of transformation between the different power levels.

Fig. 5 shows the supply-cost-curve for grid-electrification (i.e. total investments as shown in Fig. 4), expressed as the investment costs per connection, for two of these scenarios for multiple regions. This graph only contains the large countries that are singled out as regions in the IMAGE model (see Table 1) and the region of Eastern Africa as example of sub-Saharan African regions. The figure shows that that for the majority of rural households, in most regions, the cost per connection vary between 500 and 2000 USD$_{2005}$. Increasing access in areas with very low population density, such as Brazil or South Africa, can cost up to 8000 or 12,000 USD$_{2005}$ per connection. In general, regions with relatively high population density like India or Indonesia have lower costs per connection than less densely populated regions, like South Africa or Brazil.

The amount of investments that is needed to reach full access to grid-based electricity in 2030 can be determined from the full-access scenarios. Fig. 6 shows the total cumulative investments between 2010 and 2030 in rural electrification per world region in the business as usual scenario and with universal access. The ranges stem from the four different scenarios with respect to investment costs and demand levels. In Latin America, the difference between the business as usual scenario and the universal access scenario is rather small, electrification levels are already high in the business as usual scenario. In Brazil, about 36–63 billion USD$_{2005}$ would be invested under business as usual development, whereas 52–91 billion USD$_{2005}$ is required to reach universal access (or an additional 1.0–1.7 billion USD$_{2005}$ per year on top of BAU investments). For the rest of Latin America, these numbers are resp. 37–67 billion USD$_{2005}$ investments with business as usual and 91-155 billion USD$_{2005}$ for universal access (or an additional 3.3–5.4 billion USD$_{2005}$ per year).

In Asia, the majority of investments take place under business as usual projections, 96–192 billion USD$_{2005}$ cumulatively in India, and resp. 18–38 and 54–105 billion USD$_{2005}$ in Indonesia and other Asia. Under the universal access scenario, these investments are the same for India and increase to 30–59 and 66–126 billion USD$_{2005}$ in Indonesia and other Asia (or an additional of resp. 0.7–1.2 and 0.7–1.3 billion USD$_{2005}$ per year). In sub-Saharan Africa, the gap between business as usual and universal access is the largest. Cumulative investments under business as usual are expected to be 31–59 billion USD$_{2005}$ for Other sub-Saharan Africa (9–15 billion for South Africa), whereas investments for universal access in 2030 would be substantially higher and require a cumulative investment of 131–226 billion USD$_{2005}$ (and 12–19 for South Africa), or an additional 6.1–10.2 billion USD$_{2005}$ per year on top of BaU investments.

Summing the investments over these regions implies that the investments for universal access amount 477–868 billion USD$_{2005}$ for the period 2010–2030. This is an additional investment of about 238–400 billion USD$_{2005}$ cumulatively between 2010 and 2030, on top of the business-as-usual investments (thus about a doubling of these costs). To put these investments in perspective, this would be 1.8–3.3% of the total cumulative energy sector investments between 2010 and 2030 as expected by the IEA [1], or 3.6–6.5% of the global investments in the power sector in this period.

These numbers can be compared to the universal access scenario of the IEA World Energy Outlook 2010 [1]. It should be noted that

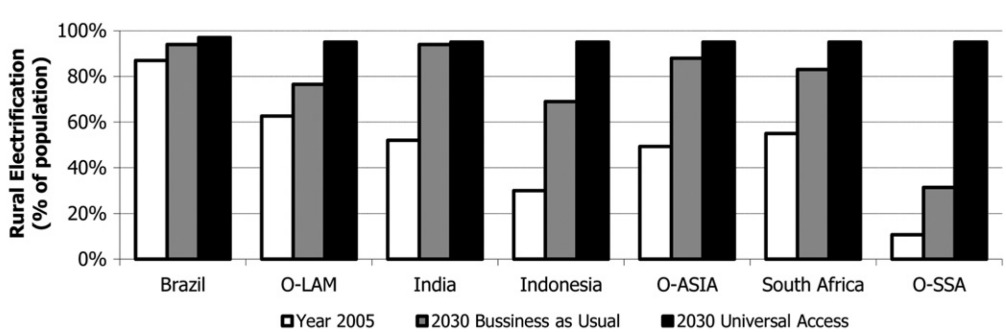

Fig. 3. Rural electrification levels in the year 2005 and projections for 2030 for the business as usual and universal access scenarios.

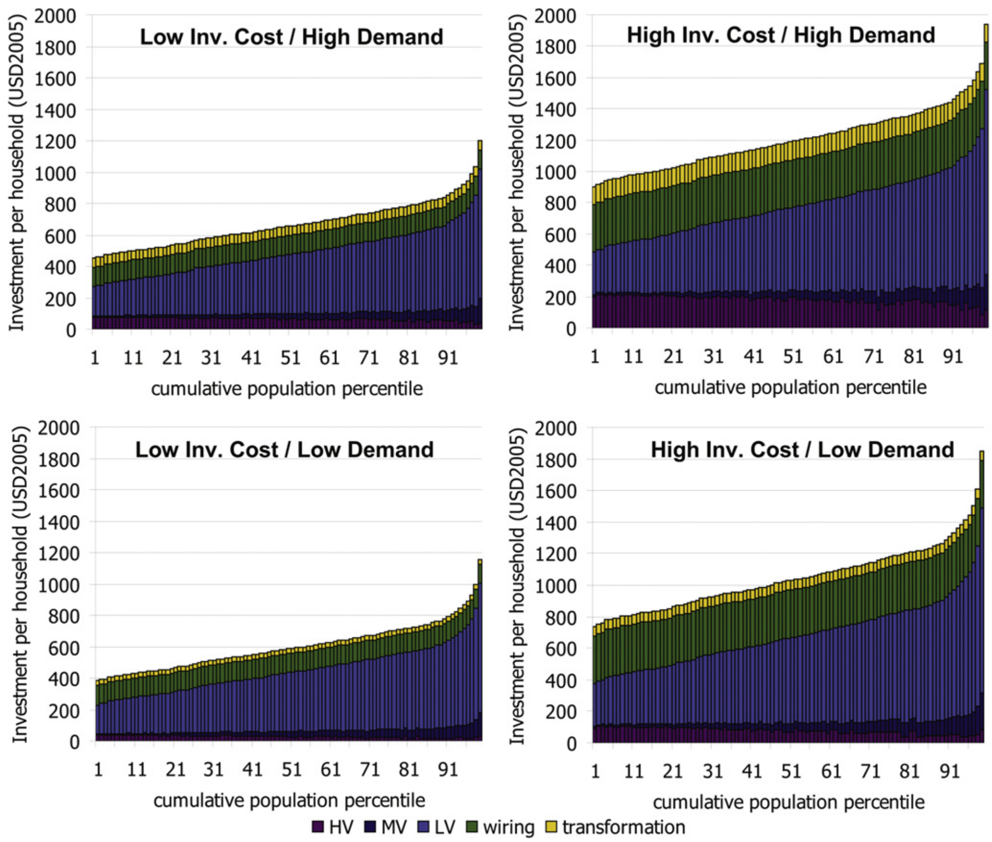

Fig. 4. Breakdown of investment costs for rural electrification in India under the four different scenarios for investment costs and household electricity demand. Investments include high voltage lines (HV), medium voltage lines (MV), low voltage line (LV), in house wiring and transformation between different voltage levels.

the IEA numbers also include investments in power generation, as well as investments for urban electrification. The cumulative investments for the period 2010–2030 in the IEA scenario amount 7 billion USD_{2005} for Latin America, 182 billion USD_{2005} for India, 158 billion USD_{2005} in Other Asia and 342 billion USD_{2005} in sub-Saharan Africa. Except for Latin America, where the IEA assumes full access to be reached almost autonomously, these numbers are higher than the results of our model as can be compared to the wider definition of costs. The global estimate of our model (477–868 Billion USD_{2005}) compares relatively well to the IEA estimate of global cumulative investment of 698 billion USD_{2005} for the period 2010–2030 to reach universal access to electricity.

4.3. Potential for mini-grid and off-grid options

The projections above are based on grid-based electricity access. However, for many villages and households it might be more attractive to apply mini-grid or off-grid power production [45–48].

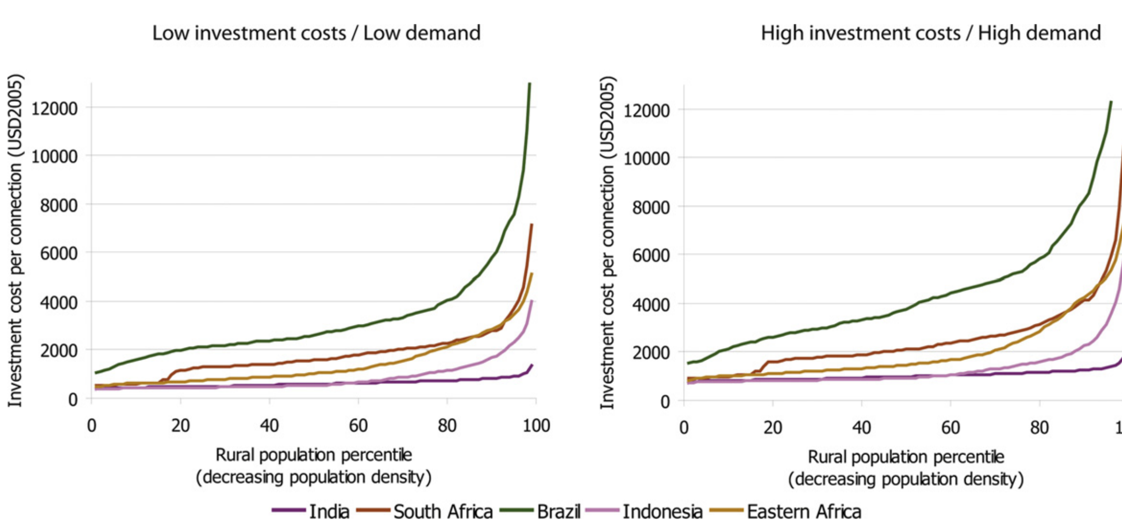

Fig. 5. Investment cost per household, for percentiles of rural population in different world regions. With decreasing population density, investment costs tend to increase sharply.

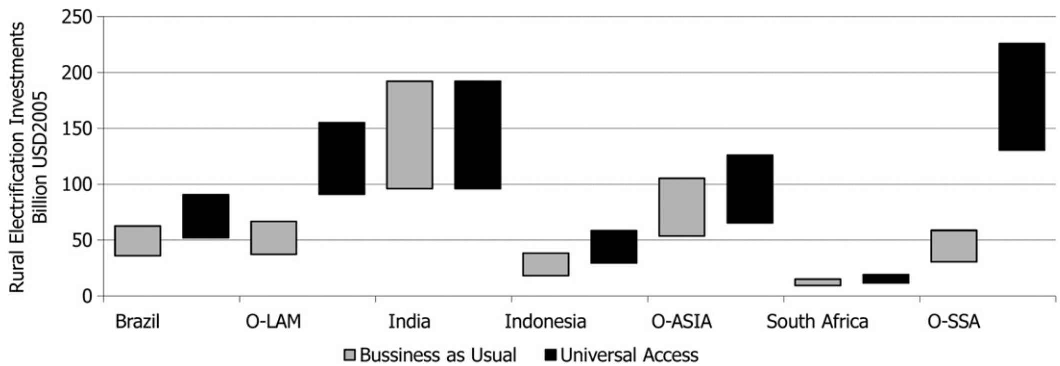

Fig. 6. Ranges for cumulative investments in rural electrification for the period 2010–2030 in the Business as Usual scenario and the Universal Access scenario. The range stems from the different scenario for investment costs and household electricity use.

From the electrification investment-cost-curve (Fig. 5) of our model, it is clear that the investment cost for grid-based electrification can reach high values, up to 8000–12,000 USD_{2005} per household. This implies that grid-based power supply is not the most attractive option for all households, and that power generation on the basis of regional (village-size) minigrids or stand-alone off-grid technologies has quite some potential as well.

Table 8 compares the costs of these technologies to electricity supplied by the centralised grid. If the costs of the alternative mini-grid or off-grid technology are lower than the grid-based electricity, we assume there is a potential for these alternative options. In Table 8, the costs of grid-based electricity are derived from the investment model and scenarios that are discussed in the previous section, with an additional 0.05 $/kWh for power generation from standard fossil technologies. The costs of minigrids only involve the costs of low-voltage lines and metering/wiring (as calculated with the model described in Section 3.3), with an additional electricity generation cost of 0.14–0.24 $/kWh for local wind or diesel based electricity [49]. Off-grid technology is assumed to be solar photovoltaic (PV), produced at 0.35–1.2 $/kWh and with added costs for wiring in the house.

Table 8 shows that there is wide divergence between regions and scenarios with respect to the potential for off-grid and mini-grid technologies. First of all, the potential for these technologies is highly dependent on the demand level. If only 65 kWh/year is used by households, the potential for alternative technologies is much higher than if 420 kWh per year is demanded. The higher the demand, the more profitable investment in a central power system becomes (as investments can be levelized over higher energy use). Hence, in the low demand scenarios, the potential for mini-grid wind or diesel, or off-grid solar PV, can reach up to 100%, if it can be generated at low costs (or if grid investment costs are assumed to be high). In scenarios with high demand for electricity, the potential drops considerably.

There is also a wide variation between regions. The investment costs for central grid-based electricity increase steeply in Brazil (Fig. 5) due to low population densities. As a result, there is quite some potential for alternative technologies: up to about 35-50% even in the high demand scenarios. The investment costs in India and Indonesia increase much less as a function of cumulative population (Fig. 5), resulting in hardly any potential for mini-grid or off-grid technologies under the high demand scenarios. In Sub-Saharan Africa, population density is also relatively low, and the potentials for non-grid technologies is considerable, up to 20–40% for South Africa, and 20–80% for Eastern Africa even in the high demand scenarios.

Table 8
Potential for minigrid and offgrid energy sources compared to grid-based electricity (assumed to be generated at 0.05 $/kWh).

	Brazil	India	Indonesia	South Africa	Eastern Africa
Low inv. cost/high demand					
Wind/diesel minigrid (0.14–0.24 $/kWh)	14–35%	1%	3–7%	10–22%	8–21%
Solar PV offgrid (0.35–1.2 $/kWh)	3–36%	1%	1–7%	2–23%	1–22%
Low inv. cost/low demand					
Wind/diesel minigrid (0.14–0.24 $/kWh)	65–100%	4–100%	25–100%	83–100%	97–100%
Solar PV offgrid (0.35–1.2 $/kWh)	62–88%	3–100%	22–100%	70–100%	95–100%
High inv. cost/high demand					
Wind/diesel minigrid (0.14–0.24 $/kWh)	29–51%	1%	5–13%	18–36%	42–78%
Solar PV offgrid (0.35–1.2 $/kWh)	7–53%	1%	1–14%	5–40%	13–82%
High inv. cost/low demand					
Wind/diesel minigrid (0.14–0.24 $/kWh)	100%	100%	100%	100%	100%
Solar PV offgrid (0.35–1.2 $/kWh)	70–100%	26–100%	36–100%	97–100%	99–100%

5. Conclusion and discussion

This paper describes the development and application of a global model for rural electrification. It first discussed the scientific literature on benefits of access to electricity and the determinants of increasing access to electricity. Based on this literature overview, we propose a global electrification trend model and an investment model for rural power grid systems. The model is applied for a set of electrification scenarios.

Obviously, the model results are influenced by various factors. Several uncertainties, caveats and assumptions of our model are worth discussing explicitly:

- We included many factors that could possibly drive electrification in our multivariate analysis, but we could only use GDP per capita, rural population density and urbanization for forward projection. For several sub-groups of countries, other variables appear to be relevant as well, but these cannot be used for long-term future projections in the context of a global energy model.
- We have used a very simple, homogenic network design to determine investments in rural electrification for all global grid cells. We tested the design and assumptions for Western European welfare levels and energy demand densities, and found results in terms of levelised T&D costs that compare well to actual levels. However, different network designs could yield different results, and hence, different investment needs.
- Given the investment needs in power supply, it seems likely that many developing countries not only have a shortage in access to electricity, they also face a lack of electricity production capacity. This extra investment need has not been taken into account in this paper.
- Our model only determines the required investment for business-as-usual and electrification target scenarios. However, it does not deal with the issue where this money should come from. The available literature on this topic implies that financing from the local community is an important aspect of successful electrification projects [31,35,50,51].
- Finally, a valuable next step in the development of this model, would be add other forms of electrification such as combination of grid and mini/off-grid options. It should be noted, however, that there are considerable uncertainty ranges both for grid-cost and minigrid/off-grid generation costs, which complicate these calculations on a generic global scale.

Based on scenario analysis with this model, we find that:

- *Trends in increasing access to electricity differ considerably between world regions*. Based on cross-country data analysis, access to electricity access occurs at lower income levels in Latin America and Asia than in Africa. Also, high rural population densities in several Asian regions lead to projections of rapidly increasing electricity access.
- *Under business-as-usual developments, universal access to electricity is not reached by 2030 in Latin America or sub-Saharan Africa, though it is in some parts of Asia.* In Latin America and Asia, the projected rural electrification levels for 2030 are around or over 80%. In sub-Saharan Africa, in contrast, the gap to universal access remains large, with only 30% electrification under business-as-usual. In the Republic of South Africa, however, this number is 83%.
- *Investments per connection depend strongly on population density*. In Latin America and sub-Saharan Africa, investment costs are relatively high. Grid-electricity systems in Asian regions are cheaper due to their high population densities.
- *Global cumulative investment to reach universal access to electricity by 2030 amount 477–868 billion USD_{2005}, or 238–400 billion above business-as-usual.* This is regionally divided in 143–246 billion USD_{2005} for Latin America, 191–377 for Asia and 142–245 billion USD_{2005} for sub-Saharan Africa. This equals 3–6% of the 16 trillion investments that will have to be made in global power supply in the same period according to IEA's World Energy Outlook.
- *The potential for mini-grid and off-grid technologies varies widely, depending on demand density, and is expected to be high in Latin America and sub-Saharan Africa, and lower in Asia.* This is closely related to population densities, which are much higher in Asian regions than in other parts of the world, but the level of electricity use per household plays an important role as well.

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