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Electrification Pathways for Tanzania: Implications for the Economy and the Environment

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Introduction

The role of energy (electricity) availability in a country's economic development is a highly relevant but also highly debated issue (e.g., Lechthaler, 2016; Lee et al., 2017; Best and Burke, 2018; Stern et al., 2019) – important factor of production and enabler of indirect effects

United Republic of Tanzania

- Average annual growth in GDP over the past decade: 6%
- Electrification rate 33%

Government plans to expand the power system (e.g., NEP, 2015; 5YDP, 2016; PSMP, 2016)

This work provides an approach to modelling alternative electrification pathways and to estimate their potential implications on the economy and the environment

The goal is to gain a better understanding of how policy decisions concerning the power sector can contribute to achieve national sustainable development goals

Introduction

Previous research has looked at biofules (Arndt et al., 2012), micro-hydro (Adebayo et al., 2013), solar energy sector (Amars et al., 2018; Aly et al., 2019), environmental assessment of electricity production (Felix and Gheewala, 2012), financial risks and barriers to electricity infrastructure (Gregory and Sovacool, 2019), institutional influence on power sector investments (Sergi et al., 2018), household energy choices (Choumert-Nkolo et al., 2019)

Outline

Electrification pathways

Modelling impacts on the economy and the environment

Results and discussion

- No changes in final demand structure
- Changes in final demand structure

Conclusions and further work

Electrification pathways

Designing electricity scenarios: 2015-2030

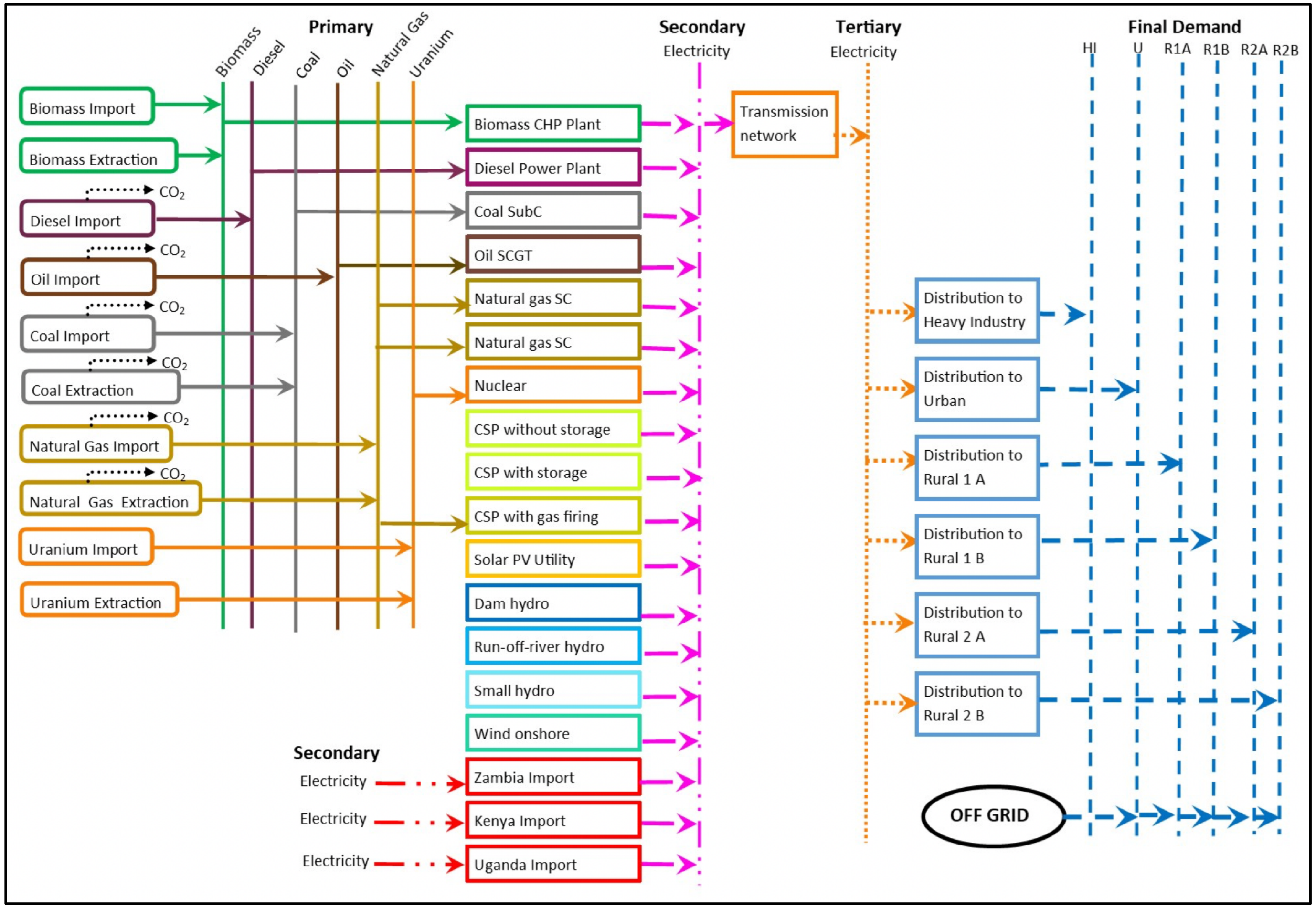
- Existing installed capacity (<2000 MW) and retirement schedule
- Technology options for future developments (on-grid and off-grid), including economic parameters for fossil fuel sources and renewable potential
- Rainfall patterns
- Carbon emission per fuel
- Cap on intermittent renewable generation (20%)
- Reserve margin (10%)

SCENARIOS (inspired by IEA World Energy Outlook)	Generation mix	Electrification rate (from 65% urban and 17% rural in 2015)	Technology/environmental policy	Solar PV and wind overnight investment cost decrease by 2040 (wrt 2015)
Business As Usual	Constant at 2015 and fixed grid rate	100% in 2050	No	40% and 10%
New Policy	Meet national targets at 2025 [PSMP, 2016]	100% in 2050	Yes (flagship projects)	40% and 10%
Energy For All	Meet national targets at 2025 [PSMP, 2016]	100% in 2030	Yes (flagship projects)	40% and 10%
450TZ	No restrictions	100% in 2050	Environmental policy (10-75 $/ton of CO_2)	70% and 25%

Modelling electricity scenarios

Open-source OSeMOSYS model

Least-cost, technically feasible technology mix, that meets electricity demands projections under a set of constraints (Howells et al. 2011)



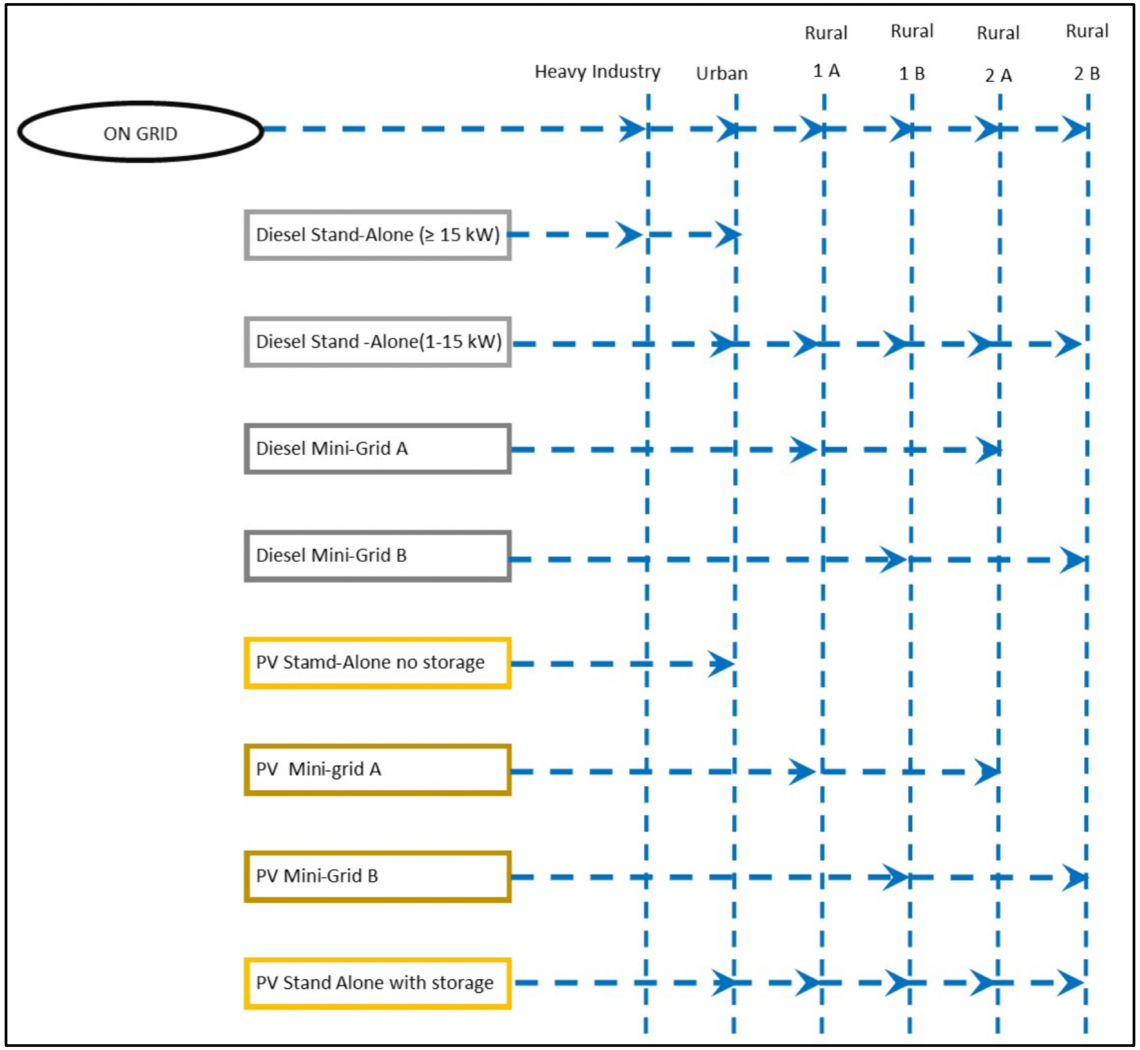
Modelling electricity scenarios

Open-source OSeMOSYS model

Least-cost, technically feasible technology mix, that meets electricity demands projections under a set of constraints (Howells et al. 2011)

Two main indicators:

- Electricity production by technology
- Annual carbon emissions from the electricity sector



Estimating electrification pathways |BAU

Installed capacity

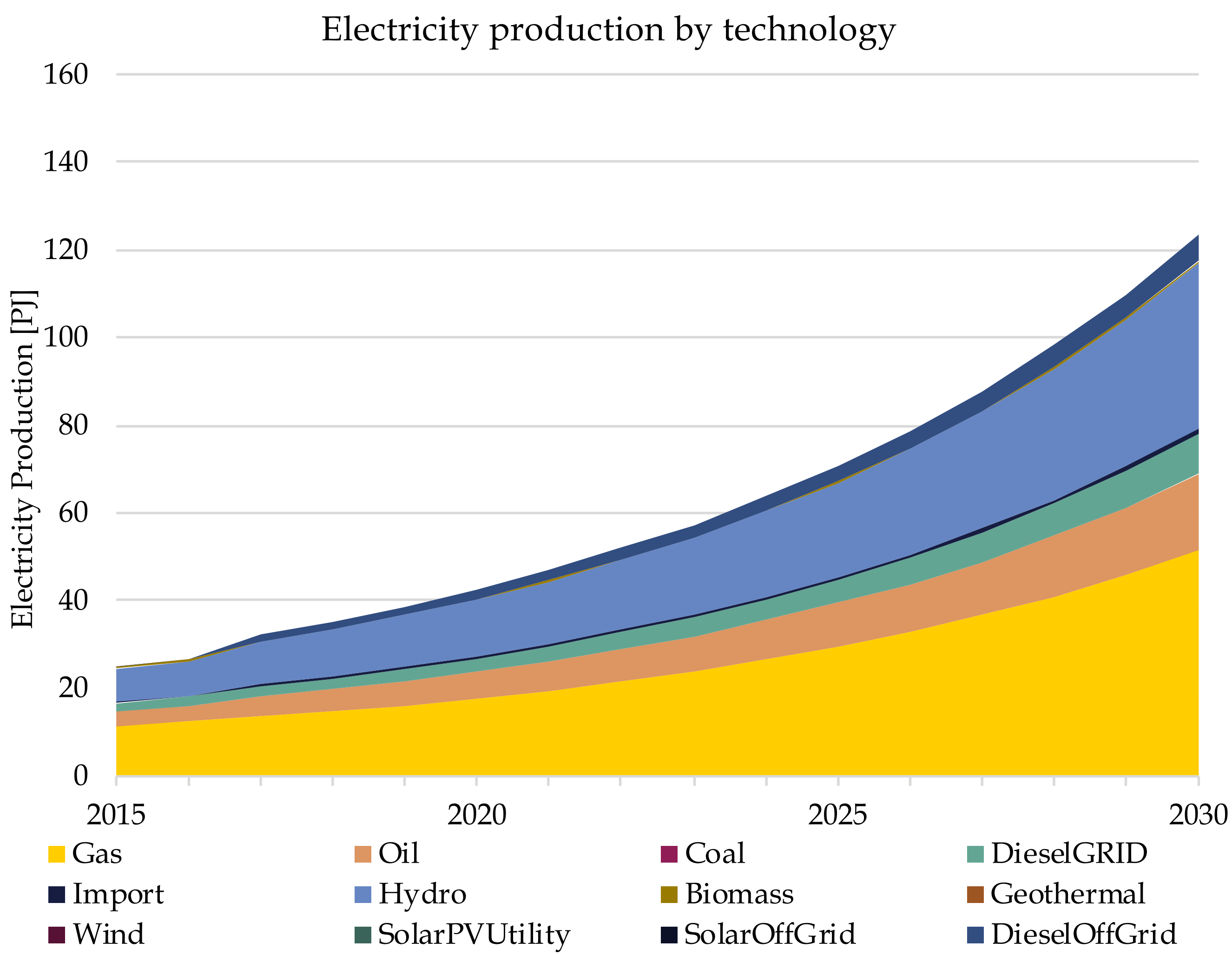
- 1,857 MW to 9,840 MW

Share of generation by technology

- Gas 45%
- Oil & Diesel 22%
- Hydro 31%
- Biomass 1%
- Diesel off-grid 0% to 5%

Annual production

- 7 TWh to 34 TWh



Estimating electrification pathways |450TZ

Installed capacity

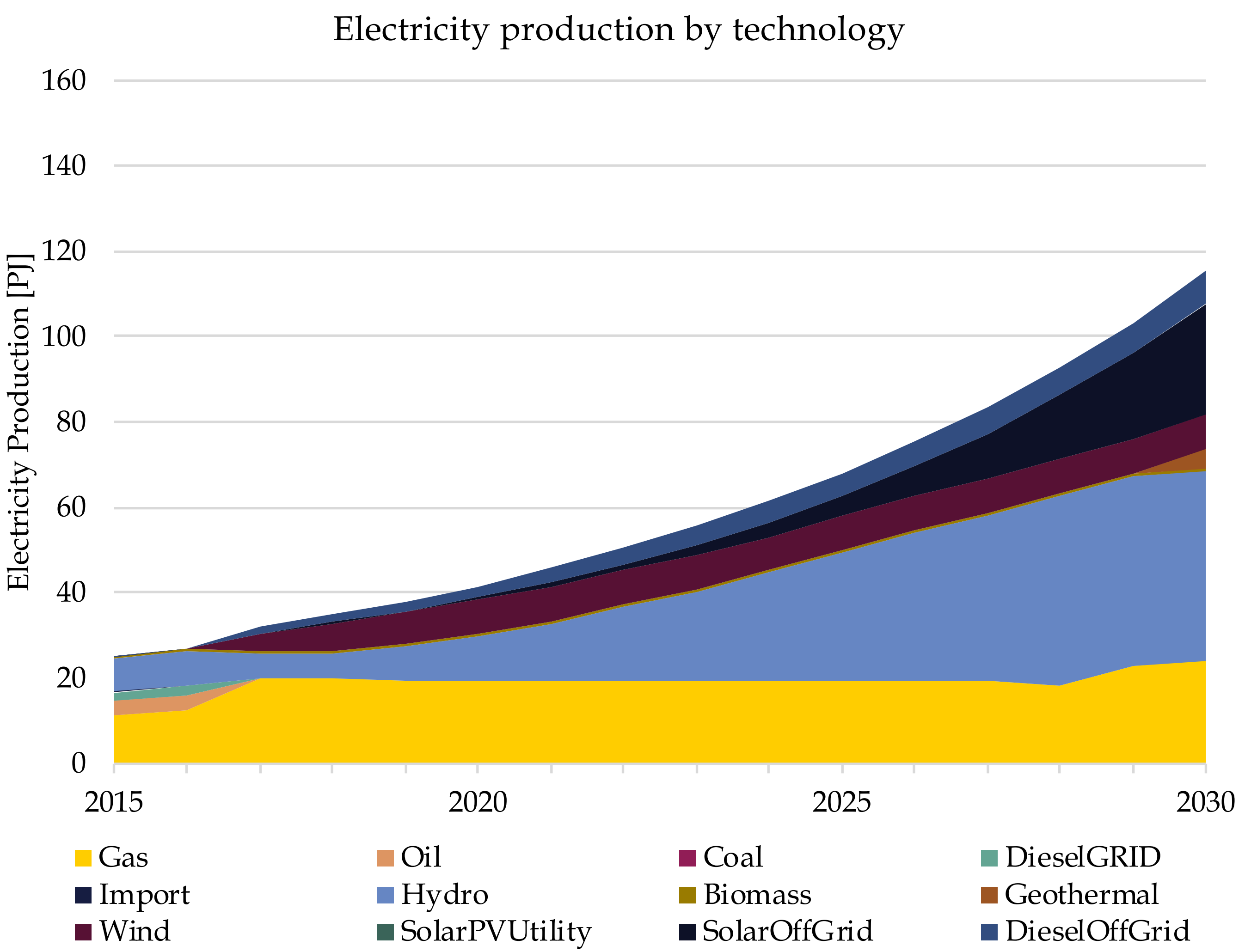
- 1,857 MW to 14,498 MW

Share of generation by technology

- Gas 45% to 21%
- Oil & Diesel 22% to 0%
- Hydro 31% to 38%
- Biomass 1%
- Geothermal 0% to 4%
- Wind 0% to 7%
- Solar PV off-grid 0% to 22%
- Diesel off-grid 0% to 7%

Annual production

- 7 TWh to 32 TWh



Estimating electrification pathways |NP

Installed capacity

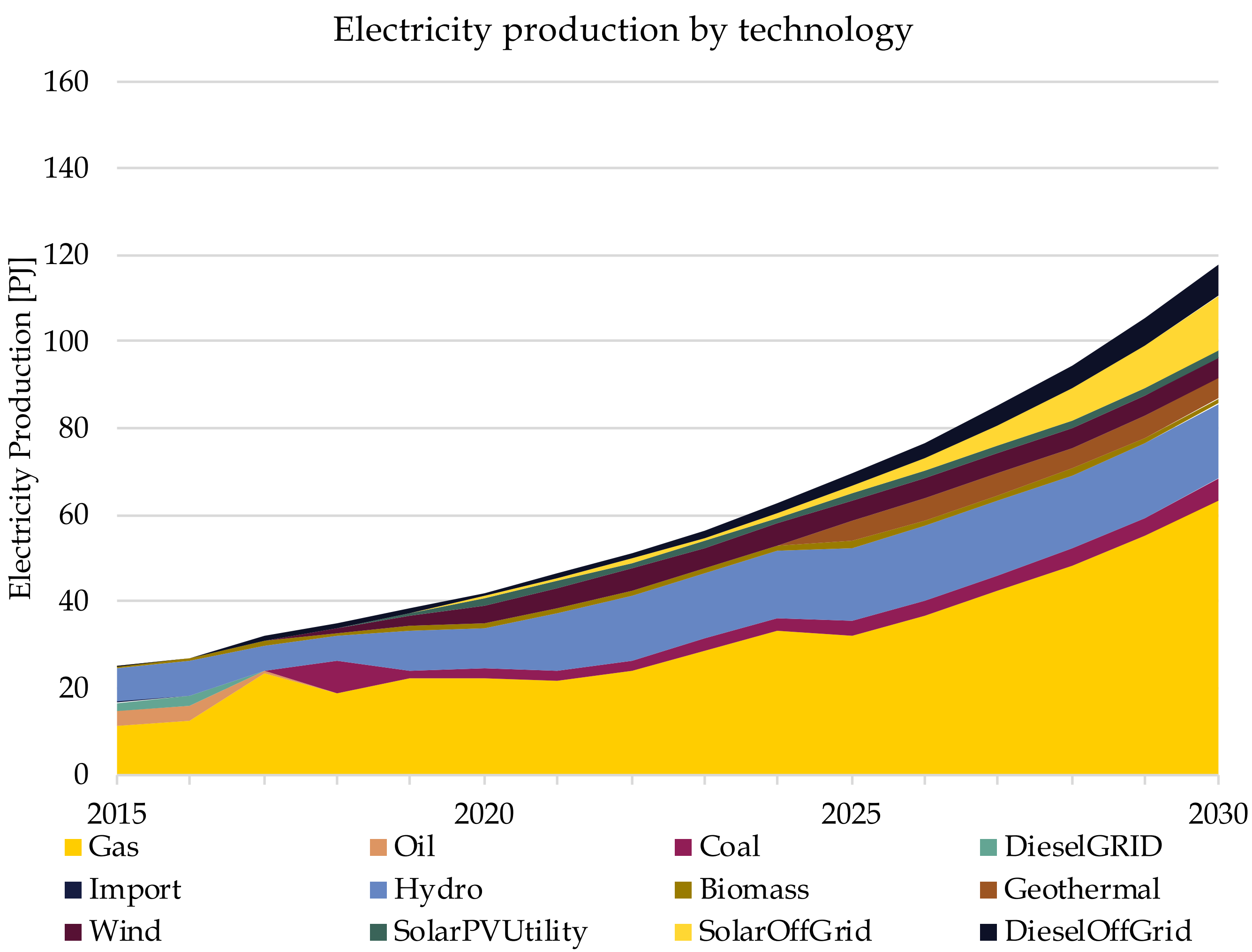
- 1,902 MW to 11,931 MW

Share of generation by technology

- Gas 45% to 54%
- Oil & Diesel 22% to 0%
- Coal 0% to 4%
- Hydro 31% to 15%
- Biomass 1%
- Geothermal 0% to 4%
- Wind 0% to 4%
- Solar PV utility 0% to 1%
- Solar PV off-grid 0% to 11%
- Diesel off-grid 0% to 6%

Annual production

- 7 TWh to 33 TWh



Estimating electrification pathways |E4A

Installed capacity

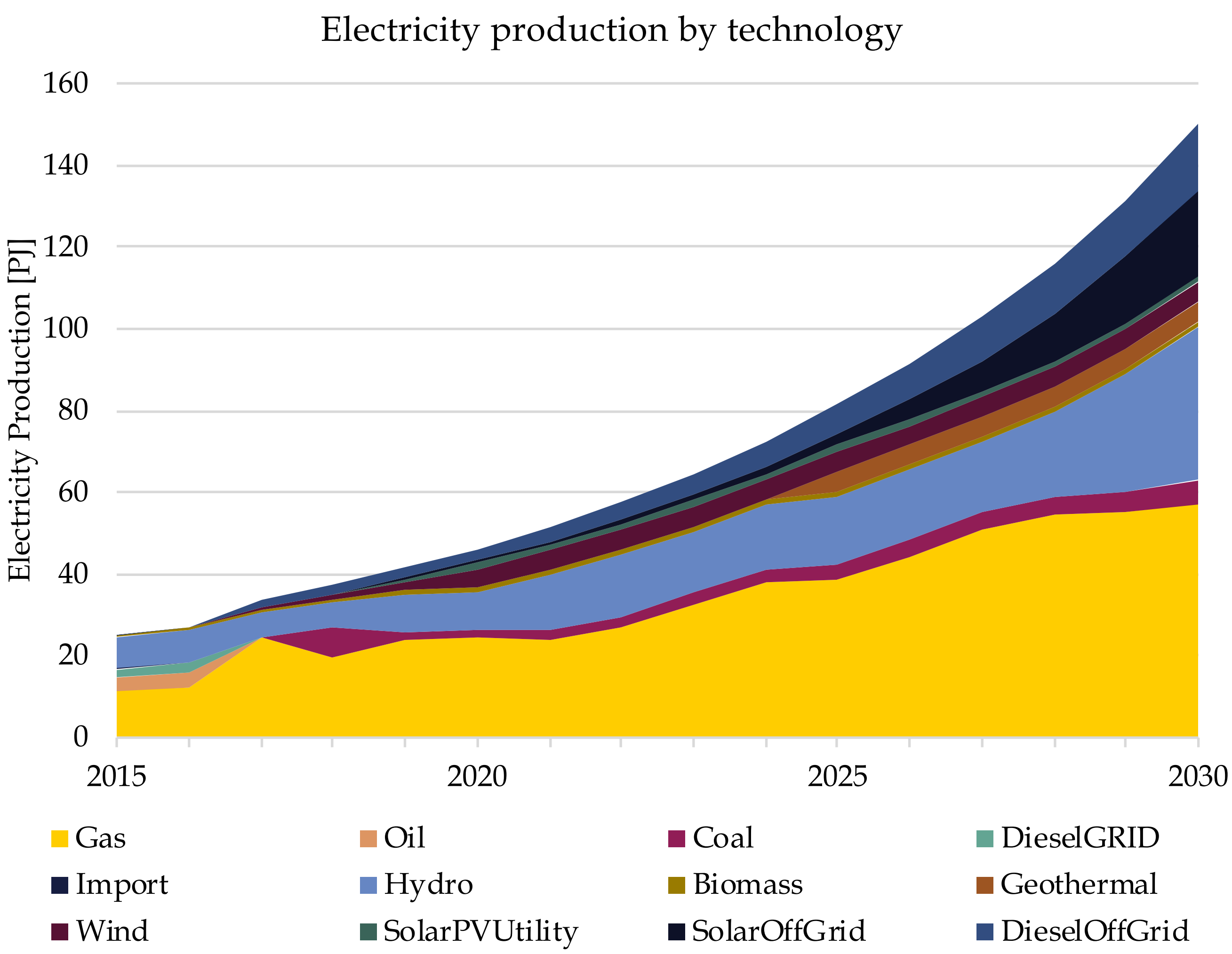
- 1,857 MW to 15,821 MW

Share of generation by technology

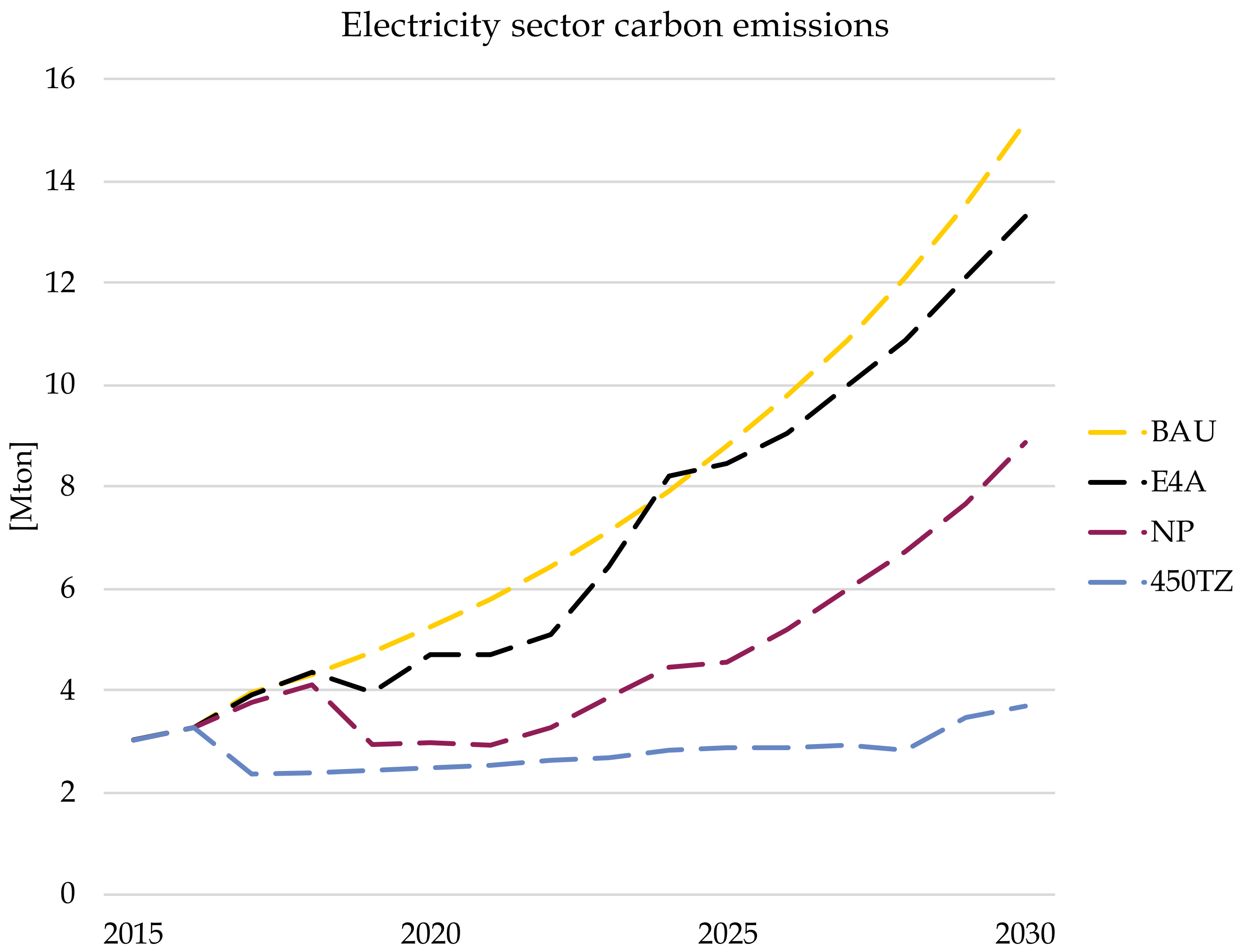
- **Gas** 45% to 38%
- Oil & Diesel 22% to 0%
- **Coal** 0% to 4%
- Hydro 31% to 25%
- Biomass 1%
- **Geothermal** 0% to 3%
- **Wind** 0% to 3%
- **Solar PV utility** 0% to 1%
- **Solar PV off-grid** 0% to 14%
- Diesel off-grid 0% to 11%

Annual production

- 7 TWh to 42 TWh



Annual carbon emissions of the electricity sector



In 2014 Tanzania was responsible for 0.59% of global CO_2 emissions

Emissions relative to GDP (carbon intensity) were almost eleven times the world average, indicating significant potential for improvement

Modelling impacts on the economy and the environment

Rationale for the analysis

Economy-wide impact of the electrification pathways is assessed via a linear optimization model based on the Leontief's Input-Output framework (Miller and Blair, 2009)

Estimate the sectoral Value-Added generation and fuel combustion-related CO_2 emissions resulting from greater electricity availability - the electricity production yield is treated as a constraint which changes over time

Trade-off between economic growth and environmental sustainability: analyse the evolution of households consumption basket and the effect on the country's carbon emissions

Tailored Leontief-Kantorovich model

$$
\begin{aligned}
max \quad & y = \mathbf{i} \cdot \mathbf{Y} \\
s.t. \quad & a: \ (\mathbf{I} - \mathbf{A}) \cdot \mathbf{x} \geq y \cdot \mathbf{s} \\
& b: \ x_{el} \leq \tilde{x}_{el} \\
& c: \ \mathbf{x} \geq 0 \ ; \ \mathbf{Y} \geq 0
\end{aligned}
$$

Optimal allocation of factors (labour and capital) able to maximize the final demand yield, y, while satisfying the given structure of the final demand (constraint *a*), with a given level of available electricity supply (constraint *b)*, and avoiding negative results (constraint *c*)

Sectoral factor use matrix $\mathbf{V}$ becomes an endogenous model result

Electricity supply a model constraint (unlimited investment capacity)

Unlimited environmental transactions

Model changes in electricity production mix and in the demand structure

Variable environmental transactions coefficients

$$
\begin{aligned}
max \quad & y = \mathbf{i} \cdot \mathbf{Y} \\
s.t. \quad & a: \quad (\mathbf{I} - \mathbf{A}) \cdot \mathbf{x} \geq y \cdot \mathbf{s} \\
& b: \quad x_{el} \leq \tilde{x}_{el} \\
& c: \quad \mathbf{x} \geq 0 \; ; \; \mathbf{Y} \geq 0
\end{aligned}
$$

To model changes in the electricity production mix, the average environmental transactions coefficients of the power sector are expressed as functions of the electricity production technology mix

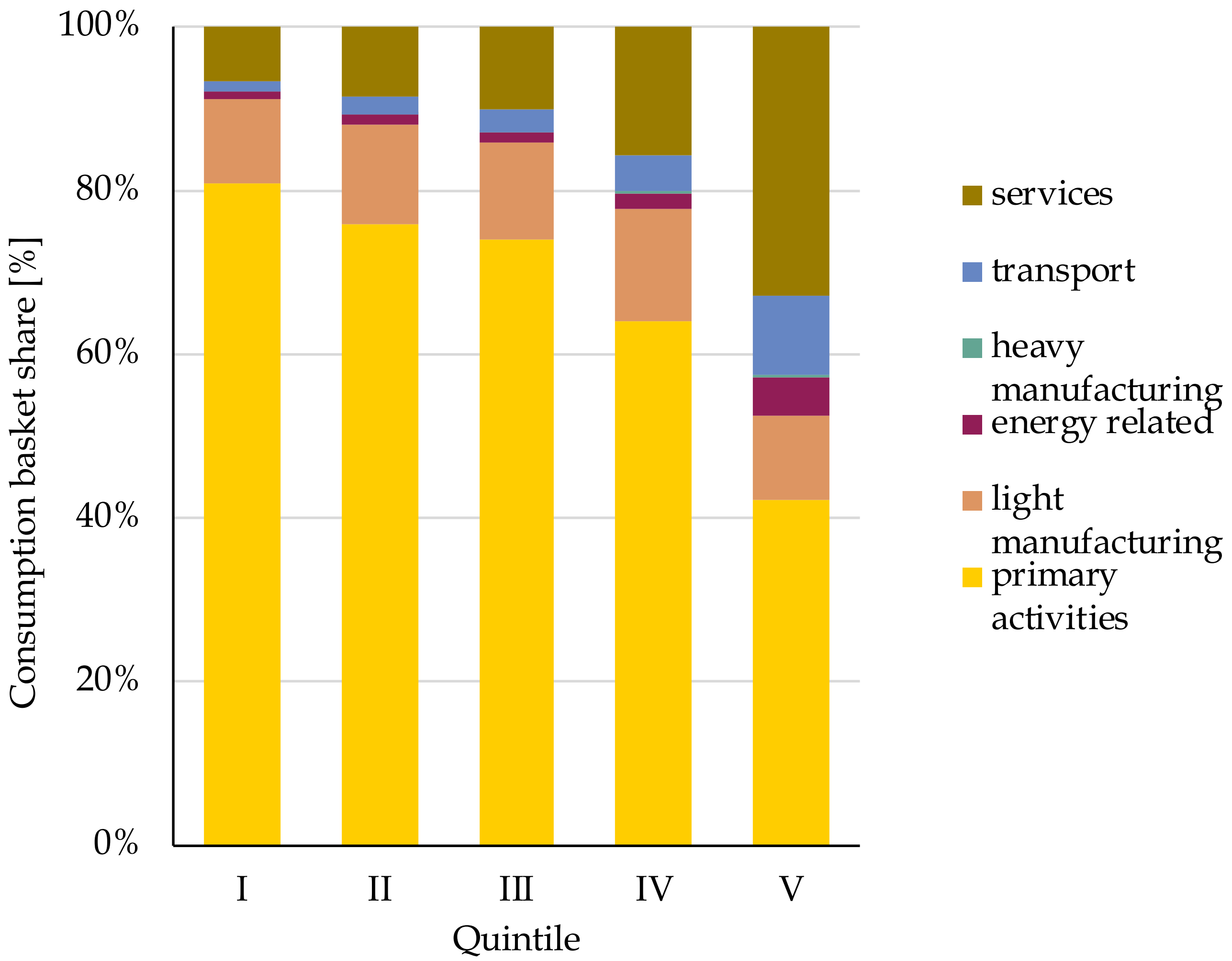
$$
\bar{\mathbf{B}}_{el} = \frac{\sum_{tech} \left(E_i \cdot \mathbf{B}_{el,i} \right)}{\sum_{tech} E_i}
$$

$\bar{\mathbf{B}}_{\mathbf{el}}(j \times 1)$	average environmental transactions coeff. power sector
E_i	electricity produced by the i-th technology over the year
$\mathbf{B}_{el,i}$	environmental transactions of the i-th technology
tech	number operative power technologies

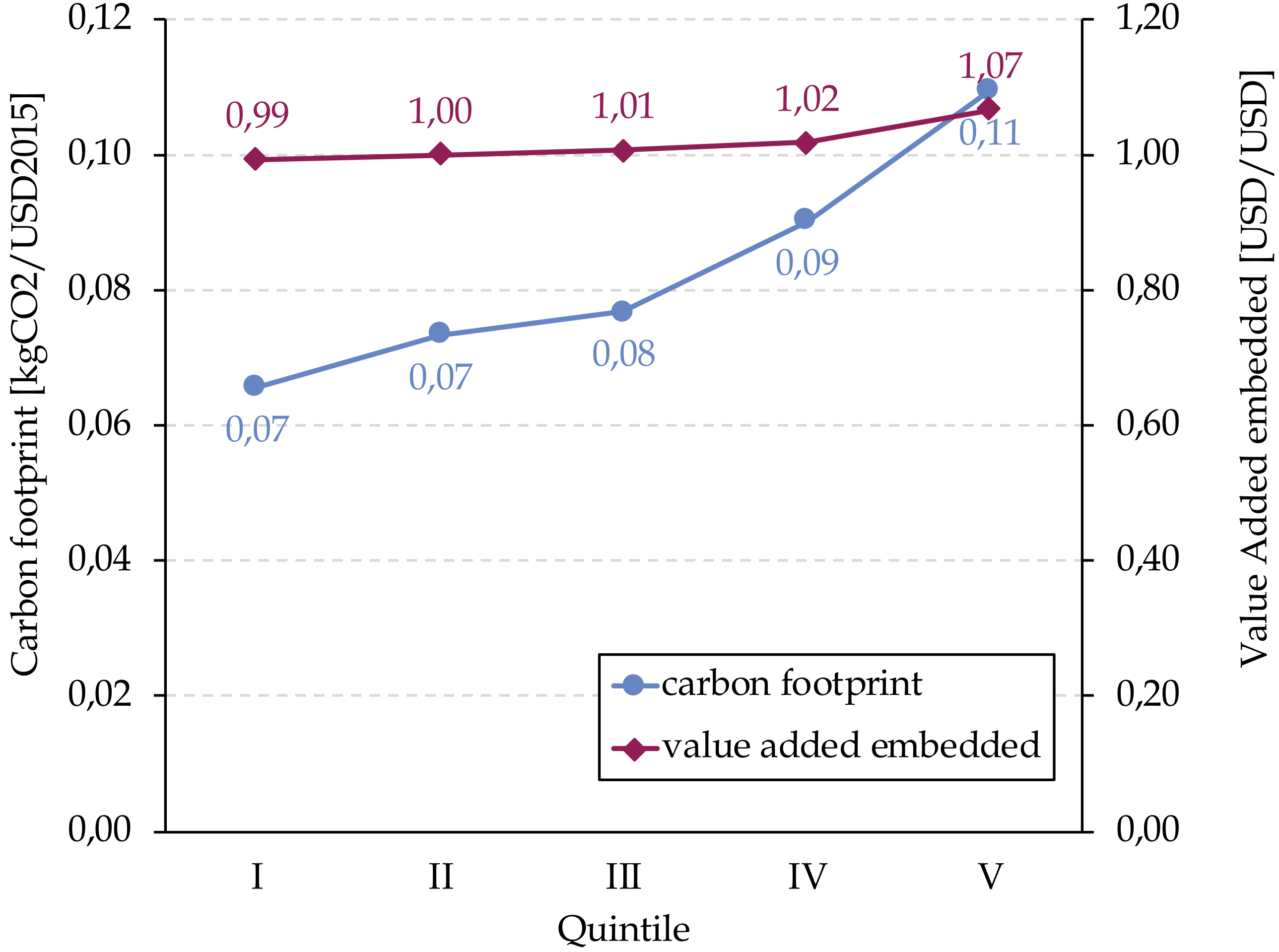
Households with different income levels: consumption baskets

Quintile	Average per capita income [2015_USD]
I	138
II	208
III	279
IV	387
V	859

Services, transport and energy amount to less than 20% of the consumption basket of lower income households



Value Added and carbon emissions embedded in one unit of household consumption



Variable final demand structure

Number of workers is constant and composed of Low- and High-Income workers: $n_W = n^i_{W,LI} + n^i_{W,HI}$

Yearly average final demand expenditures per capita for each income category $\bar{y}_{pc,LI}$ and $\bar{y}_{pc,HI}$ are known and constant

Structure of final demand of each income category $\mathbf{s}_{LI}$ and $\mathbf{s}_{HI}$ are constant

Change in overall labour compensation of Low-income workers in the i-th year

Structure of final demand in year *i* is formulated as a function of the change in workers' income from the previous year

$$\Delta V^i_{LI} = \left(\mathbf{v} \cdot \Delta \mathbf{x}^i\right) \cdot \frac{n^i_{W,LI} \cdot \bar{y}_{pc,LI}}{V^i}$$

Variable final demand structure

Number of workers is constant and composed of Low- and High-Income workers: $n_W = n_{W,LI}^i + n_{W,HI}^i$

Yearly average final demand expenditures per capita for each income category $\bar{y}_{pc,LI}$ and $\bar{y}_{pc,HI}$ are known and constant

Structures of final demand of each income category $\mathbf{s}_{LI}$ and $\mathbf{s}_{HI}$ are constant and equal to the baseline year

Change in overall labour compensation of Low-income workers in the i-th year

Number of workers that shift from low to high income category in the next year

$$\Delta n_{W,LI \to HI}^{i+1} = \frac{\Delta V_{LI}^i}{\bar{y}_{pc,HI} - \bar{y}_{pc,LI}}$$

Structure of final demand in year *i* is formulated as a function of the change in workers' income from the previous year

Variable final demand structure

Number of workers is constant and composed of Low- and High-Income workers: $n_W = n_{W,LI}^i + n_{W,HI}^i$

Yearly average final demand expenditures per capita for each income category $\bar{y}_{pc,LI}$ and $\bar{y}_{pc,HI}$ are known and constant

Structures of final demand of each income category $\mathbf{s}_{LI}$ and $\mathbf{s}_{HI}$ are constant and equal to the baseline year

Change in overall labour compensation of Low-income workers in the i-th year

Number of workers that shift from low to high income category in the next year

Number of workers in low and high income categories

$$\left.\begin{aligned} n_{W,HI}^{i+1} &= n_{W,HI}^{i} + \Delta n_{W,LI\rightarrow HI}^{i+1} \\ n_{W,LI}^{i+1} &= n_{W,LI}^{i} - \Delta n_{W,LI\rightarrow HI}^{i+1} \end{aligned}\right\} \quad n_{W,HI}^{i+1} + n_{W,LI}^{i+1} = n_W$$

Structure of final demand in year *i* is formulated as a function of the change in workers' income from the previous year

Variable final demand structure

Number of workers is constant and composed of Low- and High-Income workers: $n_W = n_{W,LI}^{i} + n_{W,HI}^{i}$

Yearly average final demand expenditures per capita for each income category $\bar{y}_{pc,LI}$ and $\bar{y}_{pc,HI}$ are known and constant

Structures of final demand of each income category $\mathbf{s}_{LI}$ and $\mathbf{s}_{HI}$ are constant and equal to the baseline year

Change in overall labour compensation of Low-income workers in the i-th year

Number of workers that shift from low to high income category in the next year

Number of workers in low and high income categories

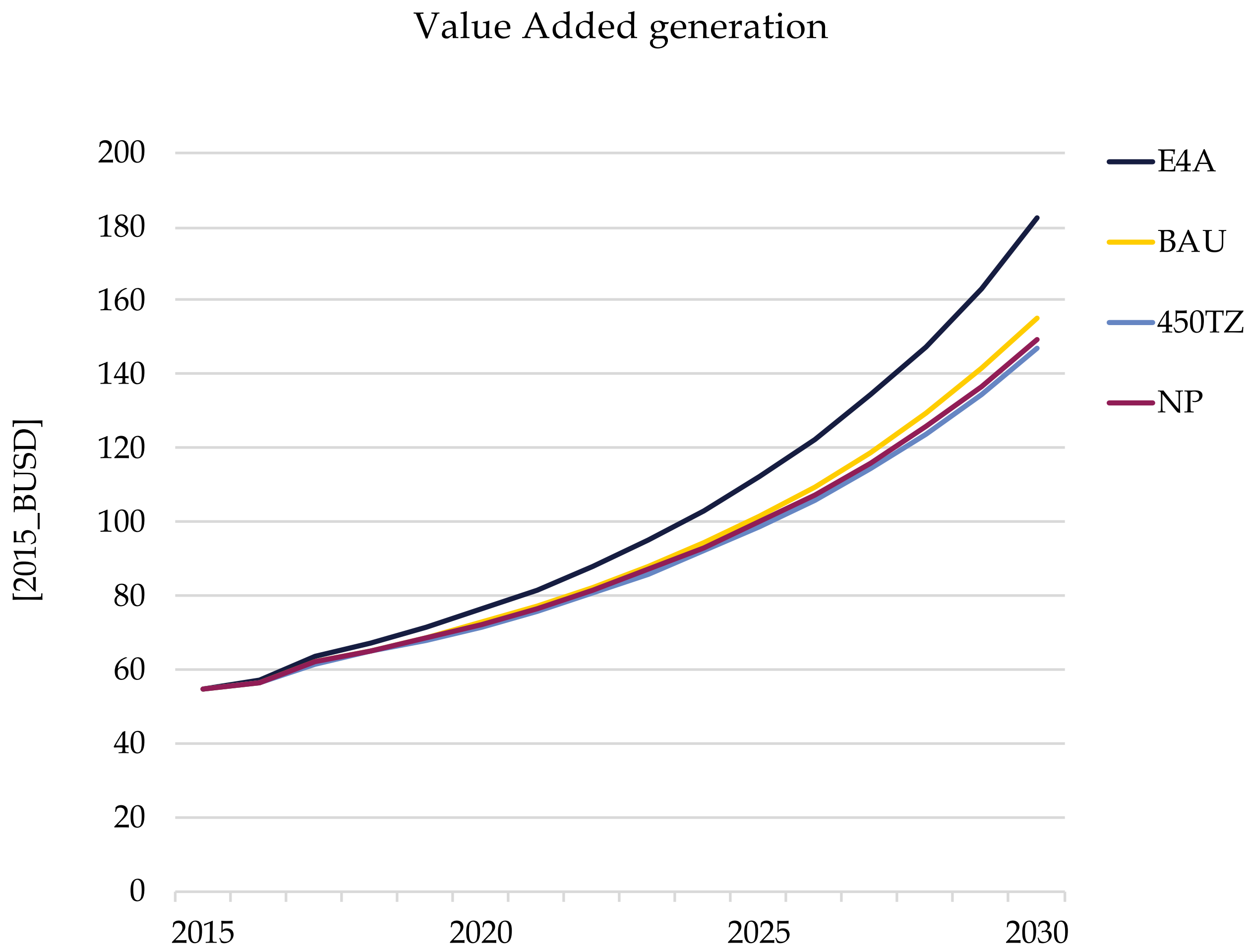
New overall structure of final demand in the next year

Structure of final demand in year *i* is formulated as a function of the change in workers' income from the previous year

$$\mathbf{s}^{i+1} = \frac{\mathbf{s}_{HI} \cdot n_{W,HI}^{i+1} + \mathbf{s}_{LI} \cdot n_{W,LI}^{i+1}}{n_W}$$

Results and discussion
No changes in final demand structure

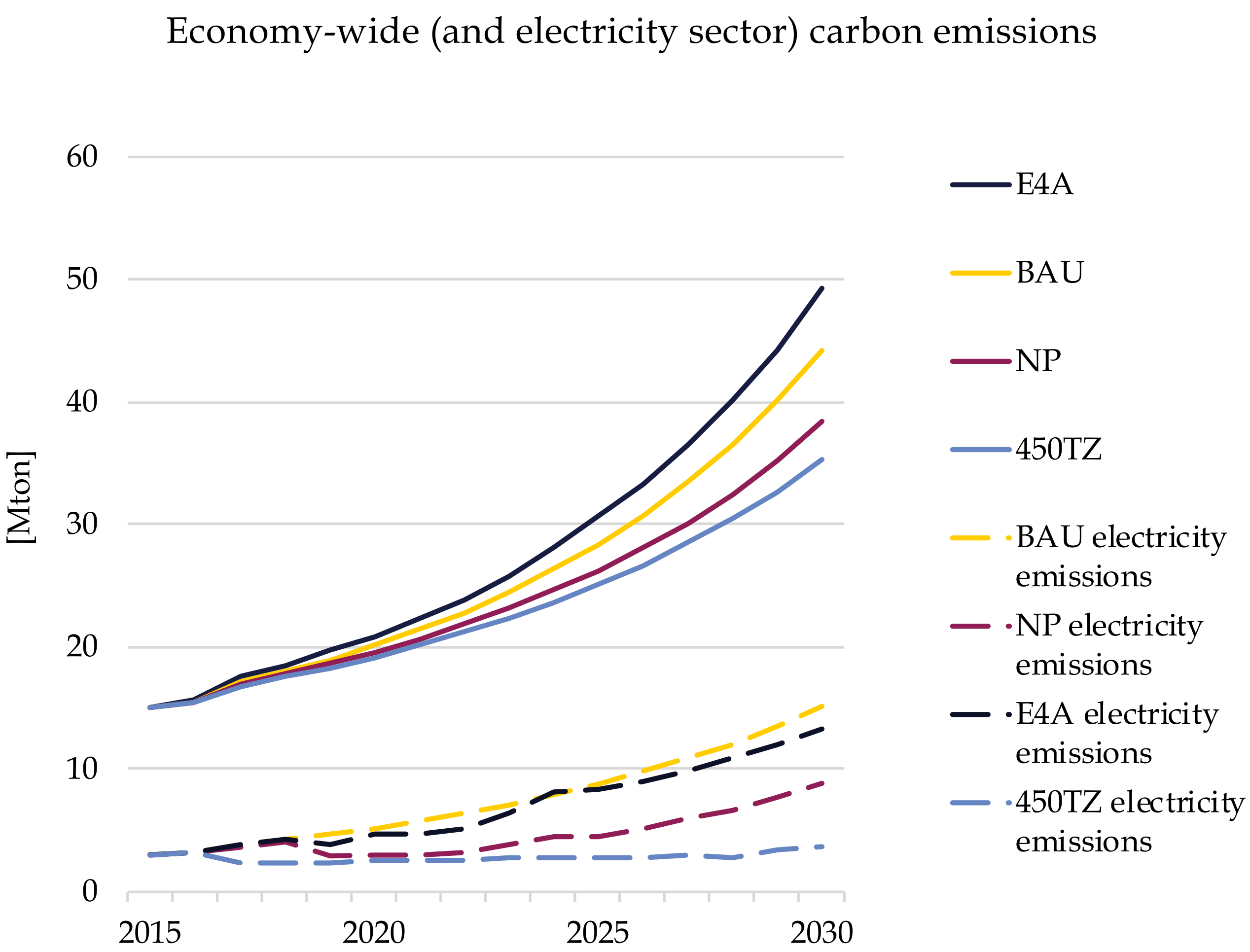
Economic growth



All electrification pathways

No changes in final demand structure

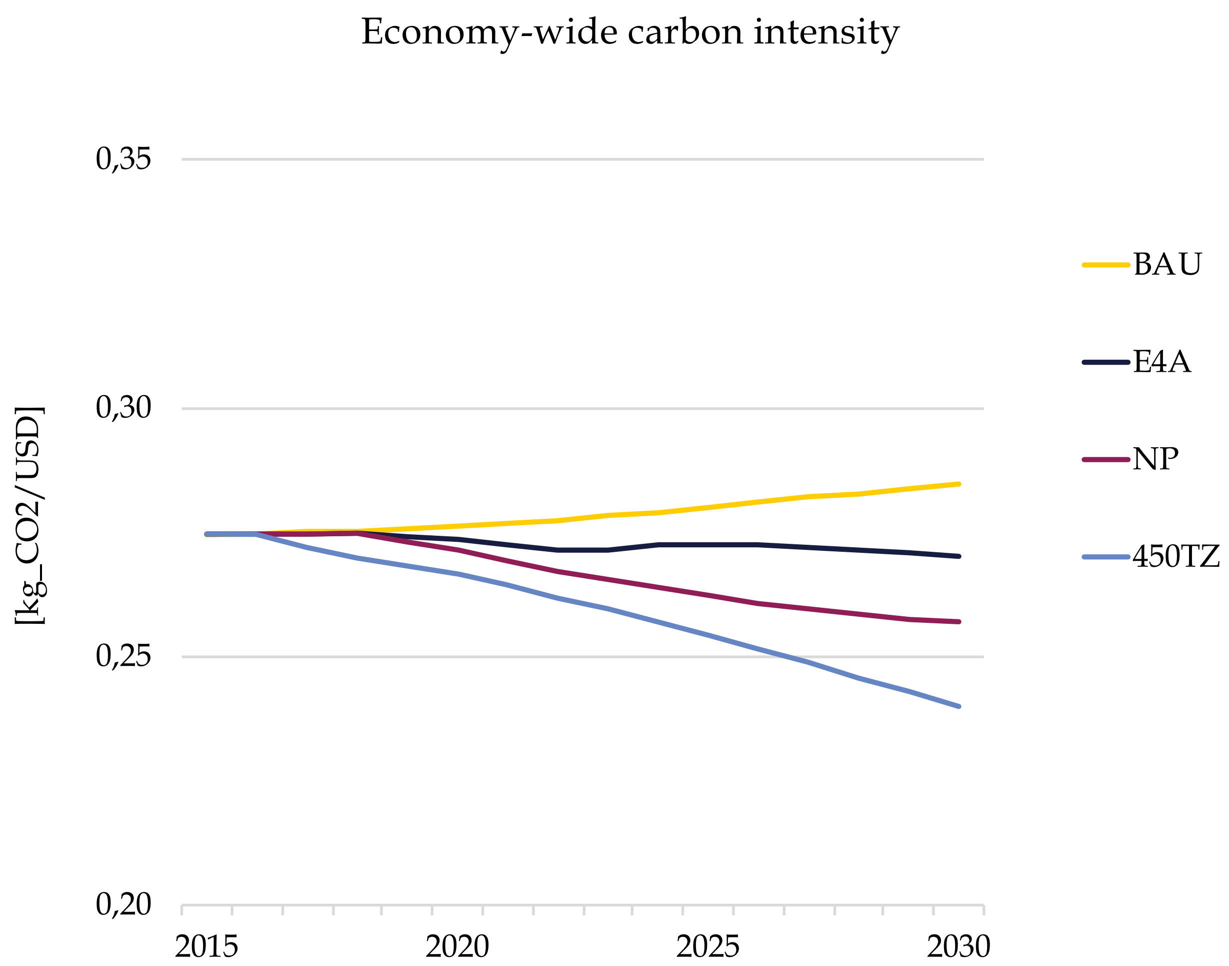
Economy-wide (and electricity sector) carbon emissions



All electrification pathways

No changes in final demand structure

Economy-wide carbon intensity



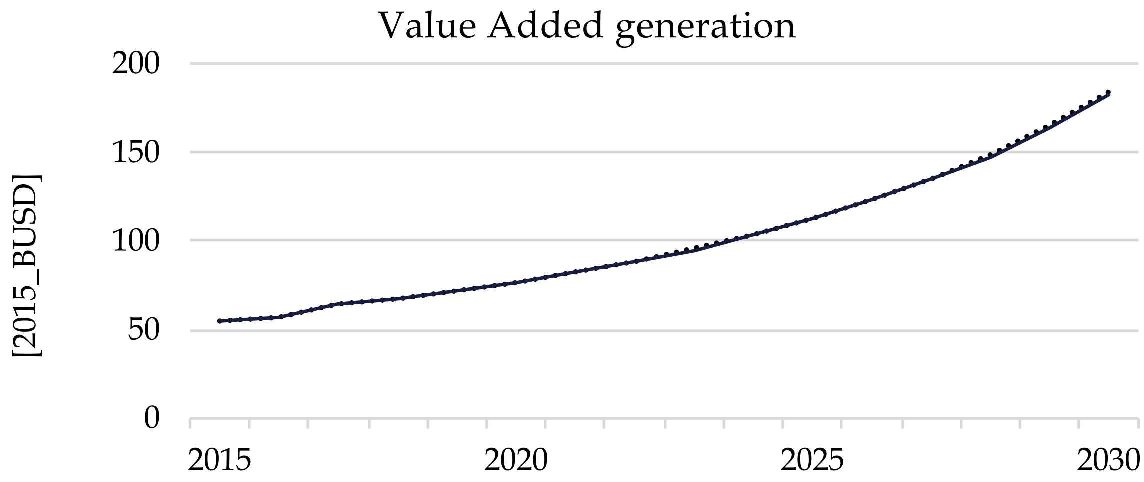
All electrification pathways

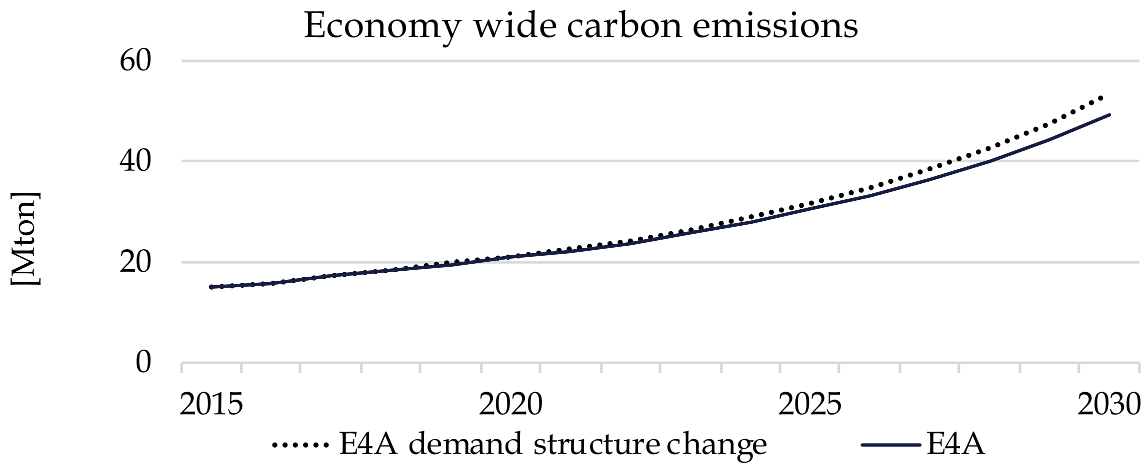
No changes in final demand structure

Results and discussion

Changes in final demand structure

Economic growth and carbon emissions economy-wide

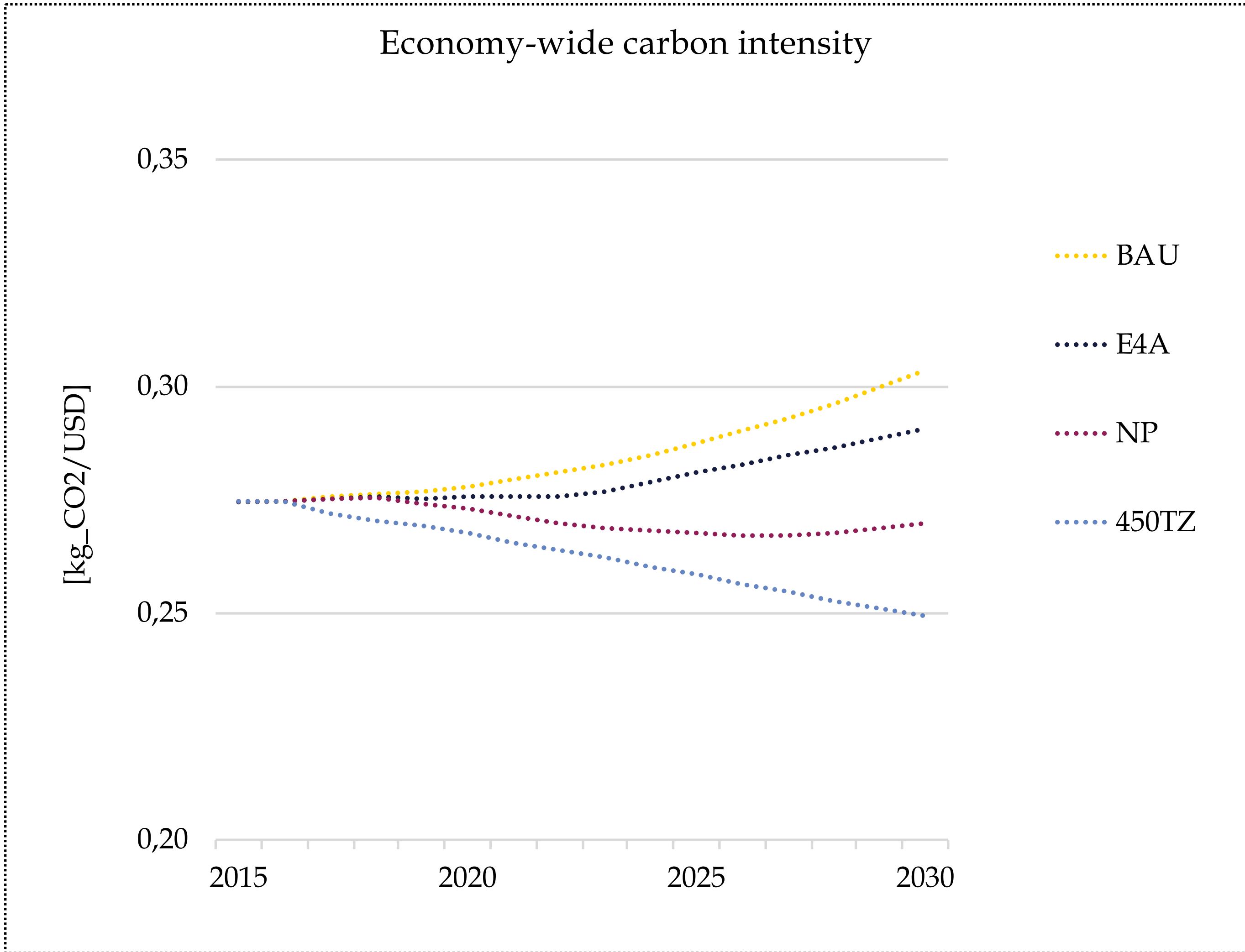




Representative pathway E4A

Changes in final demand structure

Economy-wide carbon intensity



All electrification pathways

Changes in final demand structure

Conclusions and further work

Conclusions

An expansion of the electricity sector can significantly contribute to the economic growth of the country

Associated environmental concerns might be effectively addressed in a number of ways, for instance, by relying on the country's renewable generation potential in the power sector, or specifically targeting energy efficiency and/or decarbonization efforts in the industrial sectors as well as in the provisions of services

The latter is particularly relevant as, per effect of an average income increase, household consumption behaviour contributes to drive the economy away from its traditional, agricultural base

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Questions?

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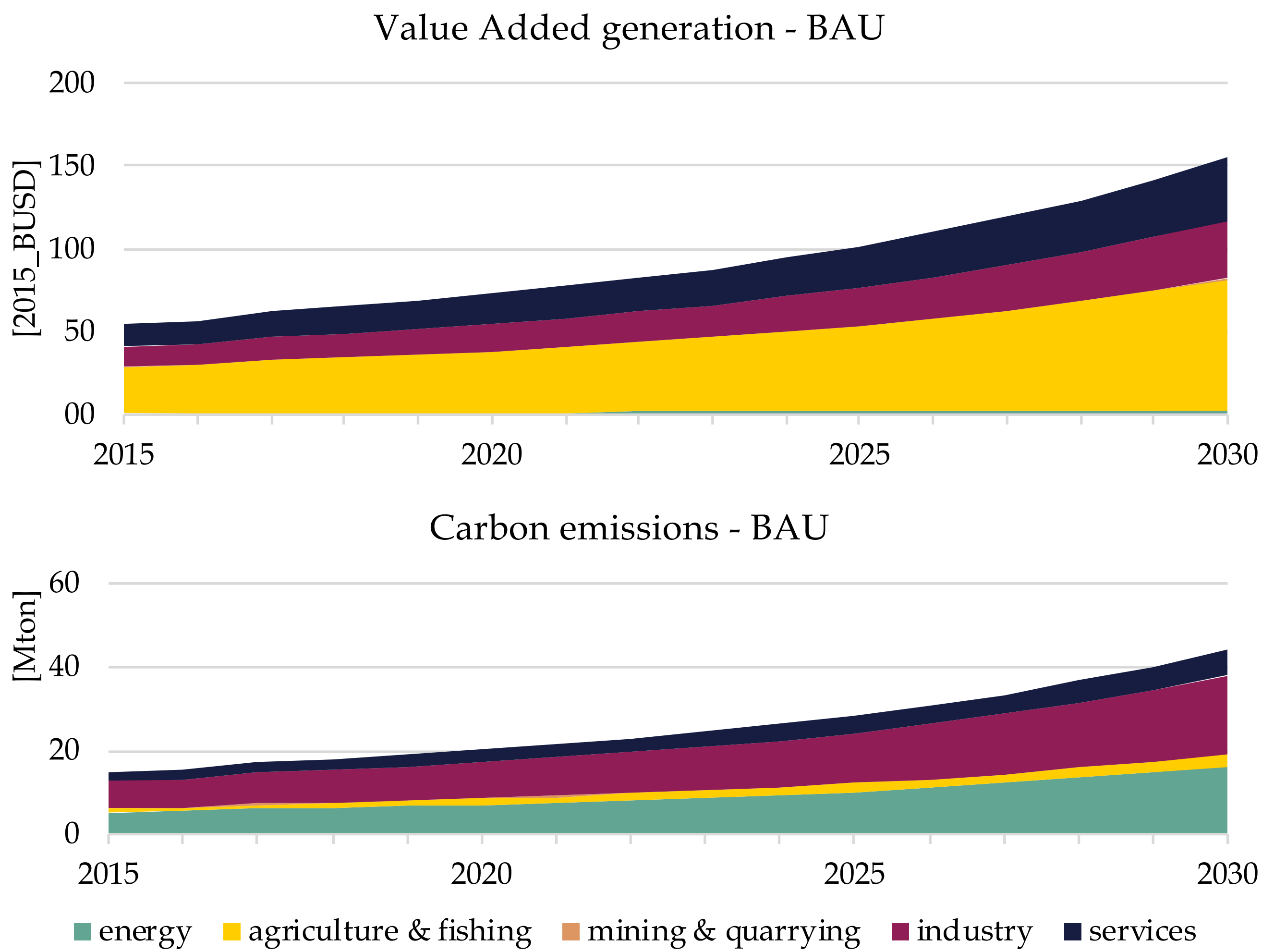
Further work

To fully explore the potential benefits and economy-wide impact of full electrification:

- characterization of household consumption, distinguishing between urban and rural consumers, as well as new accesses and capacity increases
- consider the effect of policies in other sectors of the economy, such as measures directed at energy efficiency

Several modelling improvements are possible

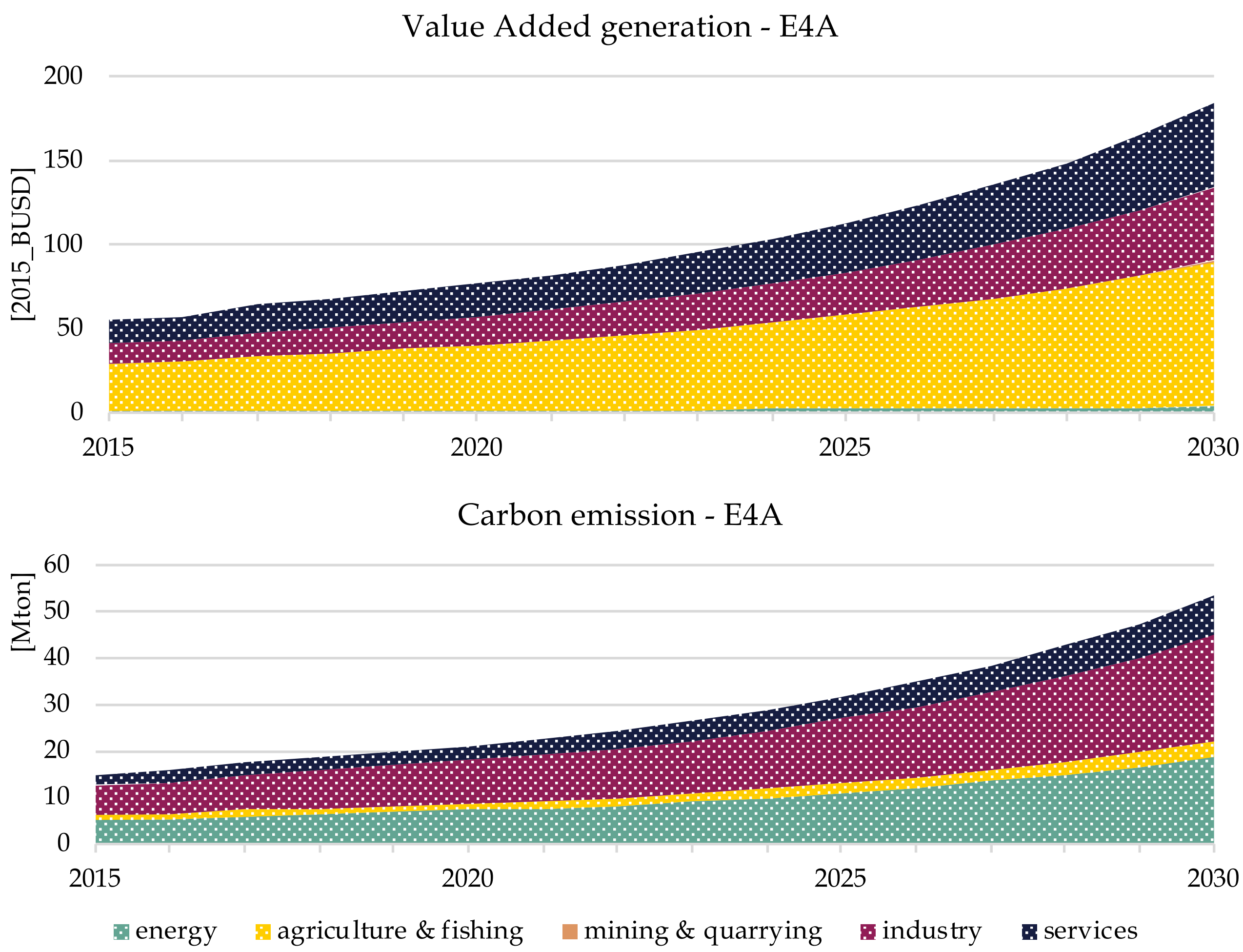
Economic growth and carbon emissions per sector



Representative pathway BAU

No changes in final demand structure

Economic growth and carbon emissions per sector



Representative pathway E4A

Changes in final demand structure

Leontief-Kantorovich model

A national economy in a given time frame

Optimal allocation of factors (e.g., labour and capital) able to maximize the final demand yield, y, while satisfying a given structure of the final demand (constraint *a*), with a given level of available primary and natural resources (constraint *b* and *c*, respectively), and avoiding negative results (constraint *d*)

Policy shocks simulated via changes, in, for instance, environmental performances, which lead to changes in overall sectoral production, hence in sectoral transaction matrices

$$
\begin{aligned}
&max && y = \mathbf{i} \cdot \mathbf{Y} \\
&s.t. && a: \; (\mathbf{I} - \mathbf{A}) \cdot \mathbf{x} \geq y \cdot \mathbf{s} \\
& && b: \; \mathbf{v} \cdot \mathbf{x} \leq V \\
& && c: \; \mathbf{B} \cdot \mathbf{x} \leq \mathbf{R} \cdot \mathbf{i} \\
& && d: \; \mathbf{x} \geq 0 \; ; \; \mathbf{Y} \geq 0
\end{aligned}
$$

$\mathbf{Y}$ $(n \times l)$	Final demand matrix
$\mathbf{A}$ $(n \times n)$	Technical coefficients matrix
$\mathbf{x}$ $(n \times 1)$	Total economic production by sector
$\mathbf{s}$ $(n \text{ x } l)$	Structure of final demand
$\mathbf{v}$ $(k \text{ x } n)$	Factor use coefficients
$\boldsymbol{V}$ $(k \text{ x } n)$	Total factor use matrix
$\mathbf{B}$ $(j \text{ x } n)$	Environmental transaction coefficients
$\mathbf{R}(j \times n)$	Environmental transaction matrix

$$
\Delta(\mathbf{A}, \mathbf{v}, \mathbf{B}, \mathbf{s})_{0 \to 1} \quad \to \quad \begin{cases} \Delta \mathbf{V} = \Delta(\mathbf{v} \cdot \hat{\mathbf{x}})_{0 \to 1} \\ \Delta \mathbf{R} = \Delta(\mathbf{B} \cdot \hat{\mathbf{x}})_{0 \to 1} \end{cases}
$$

Reference data set

This research assumes 2015 as the reference year and it is grounded on empirical meso-economic data retrieved from the Tanzanian Social Accounting Matrix (Randriamamonjy and Thurlow, 2017), developed by the International Food Policy Research Institute (IFPRI, www.ifpri.org), on other economic and social indicators retrieved in the World Bank Open Data repository (www.data.worldbank.org), on energy data retrieved from the International Energy Agency database (www.iea.org), and on sectoral CO_2 emissions retrieved from the PRIMAPHIST dataset (Gütschow et al., 2016)