Supplementary information

Achieving universal energy access while reducing energy demand? Evidence from energy-specific population projections

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1 Supplementary information about data processing

Supplementary Table 1

Table 1: Categorization of the variables for the main energy type and the main type of stove used for cooking in the Living Condition Measurement Survey Zambia 2015 dataset.

Traditional energy	charcoal purchased, charcoal own produced, collected firewood, purchased firewood, kerosine/paraffin, crop/livestock residues, coal
Modern energy	electricity, gas, solar
Traditional stove	brazier (mbaula), brick/stone stand on open fire, clay stove (mbaula), crop/livestock residues, metal stand on open fire, vehicle tyre rim
Modern stove	stove/cooker, solar, electrictiy, gas, hot plate without stand

Supplementary Table 2

Table 2: Categorization of education levels in the LCMS dataset for Zambia 2015 into education levels relevant for the micro-simulation

Education level in the LCMS dataset for Zambia 2015	Education level in the microsimulation model
Grade 1, Grade 2, Grade 3, Grade 4, Grade 5, Grade 6, Grade 7	Primary
Grade 8, Grade 9	Junior secondary
Grade 10, Grade 11, Grade 12, 12 A Levels	Senior secondary
Degree, Certificate, Diploma, Masters Degree, Doctorate	Post secondary
NA	No education

Supplementary Figure 1

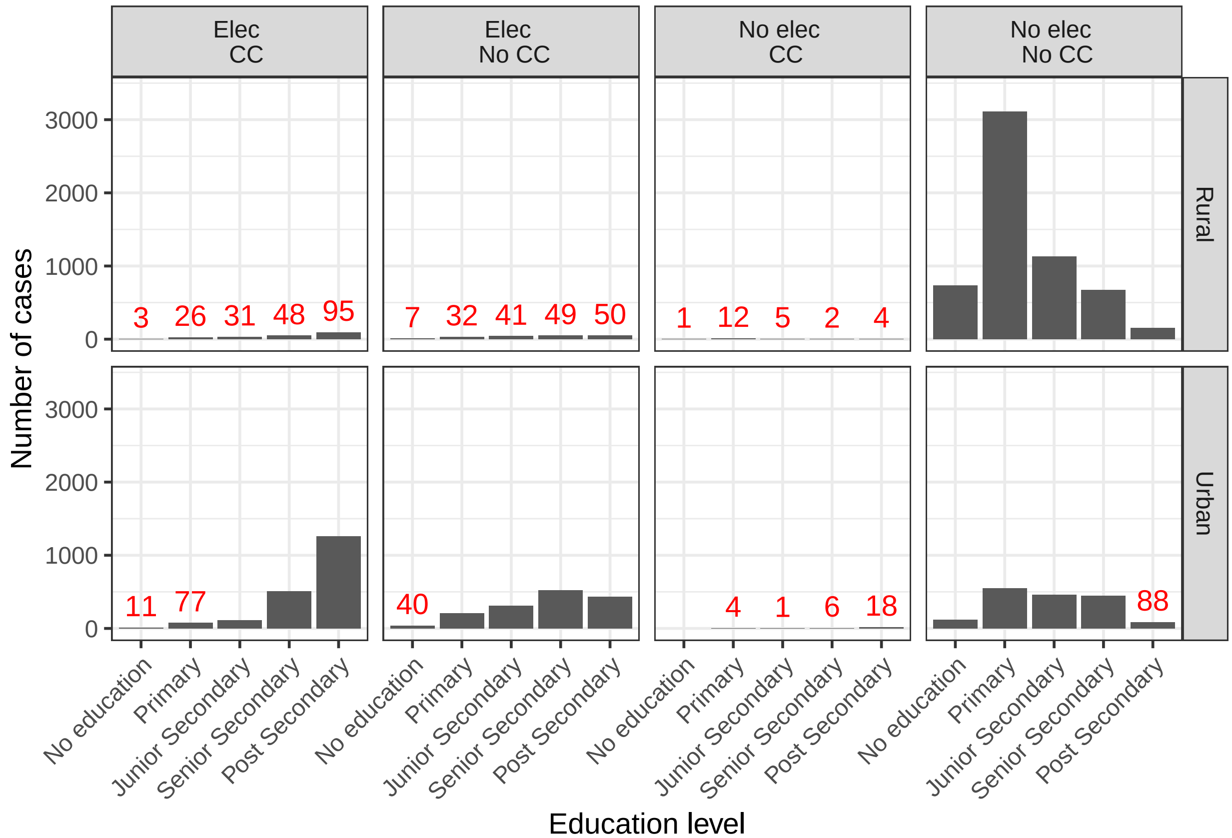

Figure 1: Number of cases in each sub-group of the LCMS dataset for Zambia 2015. The numbers in red show the number of cases for groups with less than 100 cases.

2 Calculation of emissions

Supplementary Method 1: Calculation of greenhouse gases emissions

We converted household energy use into greenhouse gas emissions using data on emissions factors, fraction of renewable biomass, global warming potential as well as projection of electricity mix for the region sub-Saharan Africa. We here provide details on the calculations. We accounted for the following greenhouse gases: carbon dioxide (CO2), methane (CH4) and nitrous dioxide (N2O), carbon monoxide (CO), Non-Volatile HydroCarbons (NMHC), black carbon (BC) and organic Carbon (OC). The conversion of charcoal and firewood into emissions required to account for the share of non-renewable biomass (Bailis et al. 2015).

For emission factors, whenever possible we used the default emission factors for stationary combustion in the residential and agriculture/forestry/fishing categories from the 2006 IPCC guidelines for national greenhouse gas inventories (IPCC 2006) (see Supplementary Table 3 and 4). When not available, we used the 1996 IPCC guidelines (IPCC 1996), and two other studies from Freeman and Zerriffi (2014) and Zavala et al. (2017).

To convert non-CO2 greenhouse gases into CO2 equivalent, we used values of global warming potential to 100 years from Arias et al. (2021), Reynolds and Kandlikar (2008) and Shindell et al. (2009) (see Supplementary Table 6). To obtain the emission factor of electricity, we needed data on the current and future electricity mix of Zambia. We used data from IRENA (IEA et al. 2021) combined with projection of electricity mix for sub-Saharan Africa from Van Vuuren et al. (2021) to project the electricity mix of Zambia until 2070.

The formula to calculate the greenhouse gas emissions (in CO2e) GHG_i for each type of energy i writes:

$$GHG_i = e_i \times \sum_g cf_{g,i} * GWP_g$$

with:

- e_i, the energy use from energy source i, in GJ (NB: for firewood and charcoal, we only account for the share of energy that is considered non-renewable, see next paragraph),
- $cf_{g,i}$, the emission factor for greenhouse gas g, for energy source i, in kg/GJ,
- GWP_g, the Greenhouse gas Warming Potential to 100 years, for gas g.

Since firewood and charcoal are not a fossil fuels and can be considered as partly renewable, we only converted into greenhouse gas emissions the share of energy use from firewood that can be considered as non-renewable. To account for that, we multiply the energy use for firewood and charcoal by the fraction of non-renewable biomass f_{NRB} (see the two equations below). We took the value for f_{NRB} for Zambia (34%) from the study of Bailis et al. (2015) (see Supplementary Table 5).

$$e_{firewood} = e'_{firewood} \times f_{NRB}$$

with:

- $e_{firewood}$, the energy use from firewood considered non-renewable,
- $e'_{firewood}$, the total energy use from firewood,
- f_{NRB}, the fraction of non-renewable biomass.

For charcoal, we first convert charcoal energy use into the equivalent in firewood energy, by multiplying the total charcoal energy use by two factors. The first factor is 3.6, which is the quantity of firewood (in kg) necessary to produce one kg of charcoal, that we took from Bailis et al. (2015). The second factor is the ratio of calorific value between firewood and charcoal. The formula to obtain the non-renewable energy use from charcoal is the following:

$$e_{charcoal} = e'_{charcoal} \times 3.6 \times \frac{NCV_{firewood}}{NCV_{charcoal}} \times f_{NRB}$$

with:

- $e_{charcoal}$, the energy use from charcoal considered non-renewable,
- $e'_{charcoal}$, the total energy use from charcoal,
- f_{NRB}, the fraction of non-renewable biomass.

Emissions from electricity depend on the way electricity is generated, which depends from one country to the other. To calculate emissions from electricity, we adopted the following steps. First, we calculated the percentage of non-renewable energy in the electricity source mix of Zambia, using 2020 data from IRENA (IEA et al. 2021).

Second, we estimated how renewable energy will develop in the future in Zambia. Since projections specific to Zambia do not exist, we used data from Van Vuuren et al. (2021) to obtain the percentage change in renewable energy source in the electricity mix of sub-Saharan Africa, using the SSP2 projection. We then obtained a percentage of renewable energy in the electricity source mix for Zambia until 2070.

Third, we calculated the average CO2 factor for non-renewable sources of electricity. Finally, we calculated the average CO2 factor of electricity for every 5-year time step using the projected percentage of renewable in the electricity source mix, and the average CO2 factor for non-renewable sources of electricity, as follows:

$$ef_{elec,t} = p_{NRB_{elec,t}} \times \frac{\sum_s ef_{NRB_s}}{S}$$

with:

- $ef_{elec,t}$, the emission factor for electricity in Zambia for timestep t,
- $p_{NRB_{elec,t}}$, the percentage of non-renewable energy in the electricity source mix of Zambia at time step t and
- $\frac{\sum_s ef_{NRB_s}}{S}$, the average emission factor of non-renewable energy source for electricity production in Sub-Saharan Africa, across S sources.

Supplementary Tables 3, 4, 5 and 6: Values and data sources for emission factors, fNRB and GWP

Table 3: Emission factors in kg/GJ for different energy sources and greenhouse gases. Data sources: see Supplementary Table 4.

Fuel	CO2	CH4	NO2	CO	NMHC	BC	OC	SO2
Coal	97.5	0.300	0.0015	0.9985507	0.0772947	0.1487923	0.1135266	0.0072464
Firewood	112.0	0.300	0.0040	5.0000000	0.6000000	0.0705128	0.1378205	0.0173077
Charcoal	112.0	0.200	0.0010	7.0000000	0.1000000	0.0061017	0.0084746	0.0135593
Kerosene	71.9	0.010	0.0006	0.1289954	0.1152968	0.0006849	0.0009132	0.0006849
LPG	63.1	0.005	0.0001	0.0780127	0.1553911	0.0014799	0.0014799	0.0000000
Gas	56.1	0.005	0.0001	0.0500000	0.0500000	0.0014583	0.0014583	0.0000000
Diesel	74.1	0.010	0.0006	1.0000000	0.2000000	0.0200581	0.0288372	0.0069280
Paraffin	73.3	0.010	0.0006	0.1289954	0.1152968	0.0006849	0.0009950	0.0007463

Table 5: Data for fraction of Non-Renewable Biomass (fNRB), Wood equivalent and Net Calorific Values for different energy sources. Source: Bailis et al. 2015 for fNRB and wood equivalent, IPCC 2006 default, Table 1.2, for NCV.

Fuel	fNRB	Wood equivalent	NCV (GJ/t)
Coal	1.00	NA	20.7
Firewood	0.34	1.0	15.6
Charcoal	0.34	1.9	29.5
Kerosene	1.00	NA	43.8
LPG	1.00	NA	47.3
Gas	1.00	NA	48.0
Diesel	1.00	NA	43.0
Paraffin	1.00	NA	40.2

Table 6: Data for Global Warming Potential to 100 years, for different greenhouse gases, and their source

Gas	GWP100	Source
CO2	1.0	IPCC AR6
CH4	27.9	IPCC AR6
NO2	273.0	IPCC AR6
CO	2.2	IPCC AR5, Table 8.A.4
NMHC	3.4	IPCC AR4
BC	900.0	Reynolds and Kandlikar 2008
OC	-35.0	Reynolds and Kandlikar 2008
SO2	-30.0	Shindell et al. 2009

Table 4: Data sources for emission factors for different energy sources and greenhouse gases. For all values taken from Freeman and Zerriffi (2014) and Zavala et al. (2017), the values were divided by the corresponding Net Calorific Values found in Table 5. Values: see Supplementary Table 3.

Fuel	**CO2**	**CH4**	**NO2**	**CO**	**NMHC**	**BC**	**OC**	**SO2**
Coal	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1
Firewood	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	IPCC 1996 default	IPCC 1996 default	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1
Charcoal	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	IPCC 1996 default	IPCC 1996 default	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1
Kerosene	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1
LPG	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1
Gas	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	IPCC 1996 default	IPCC 1996 default	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1
Diesel	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	IPCC 1996 default for road transportation	IPCC 1996 default for road transportation	Zavala et al. 2017, averaged on Table 2	Zavala et al. 2017, averaged on Table 2	Zavala et al. 2017, averaged on Table 2
Paraffin	IPCC 2006 default	IPCC 2006 default	IPCC 2006 default	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1	Freeman and Zerriffi 2014, Table S1

Supplementary Figure 2: Greenhouse gas emissions

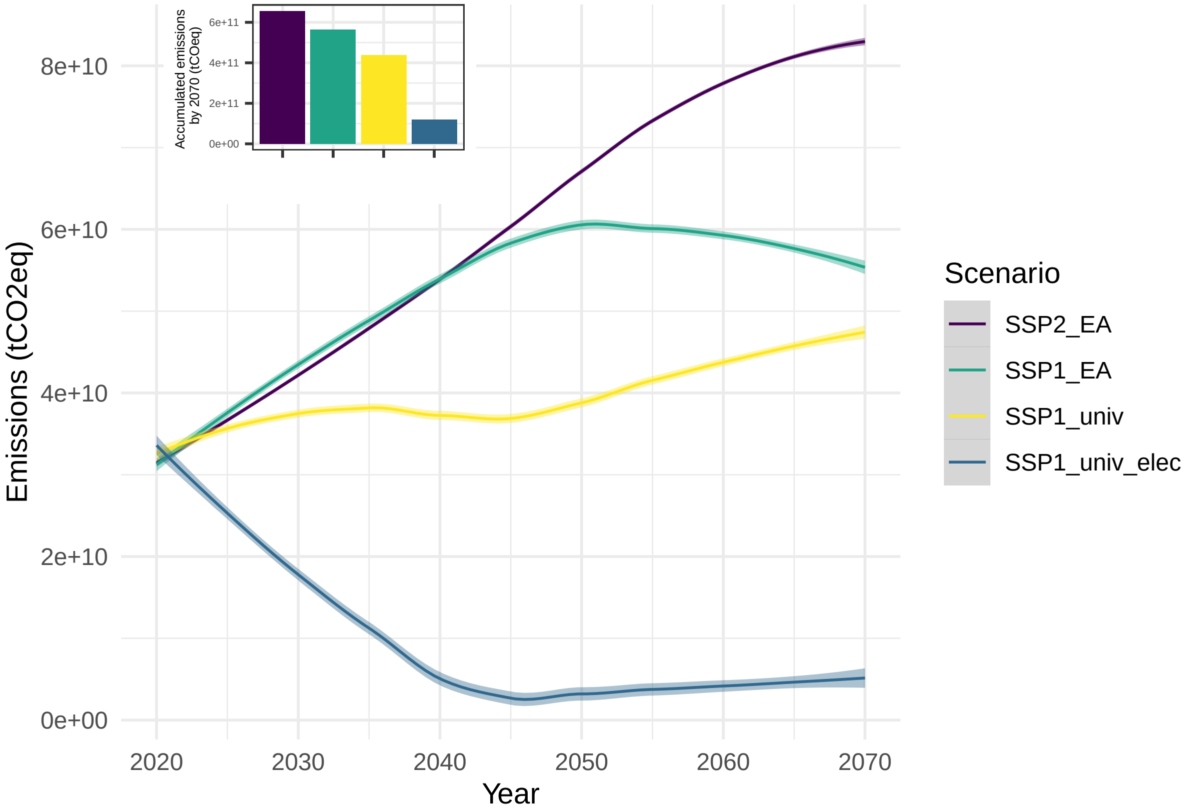

Figure 2: Emissions of the population under four scenarios. Inset: Cummulated emissions in 2070 under four scenarios.

90 # 3 Validation

91 ## Supplementary Figures 3 and 4: Validation of the education pathways

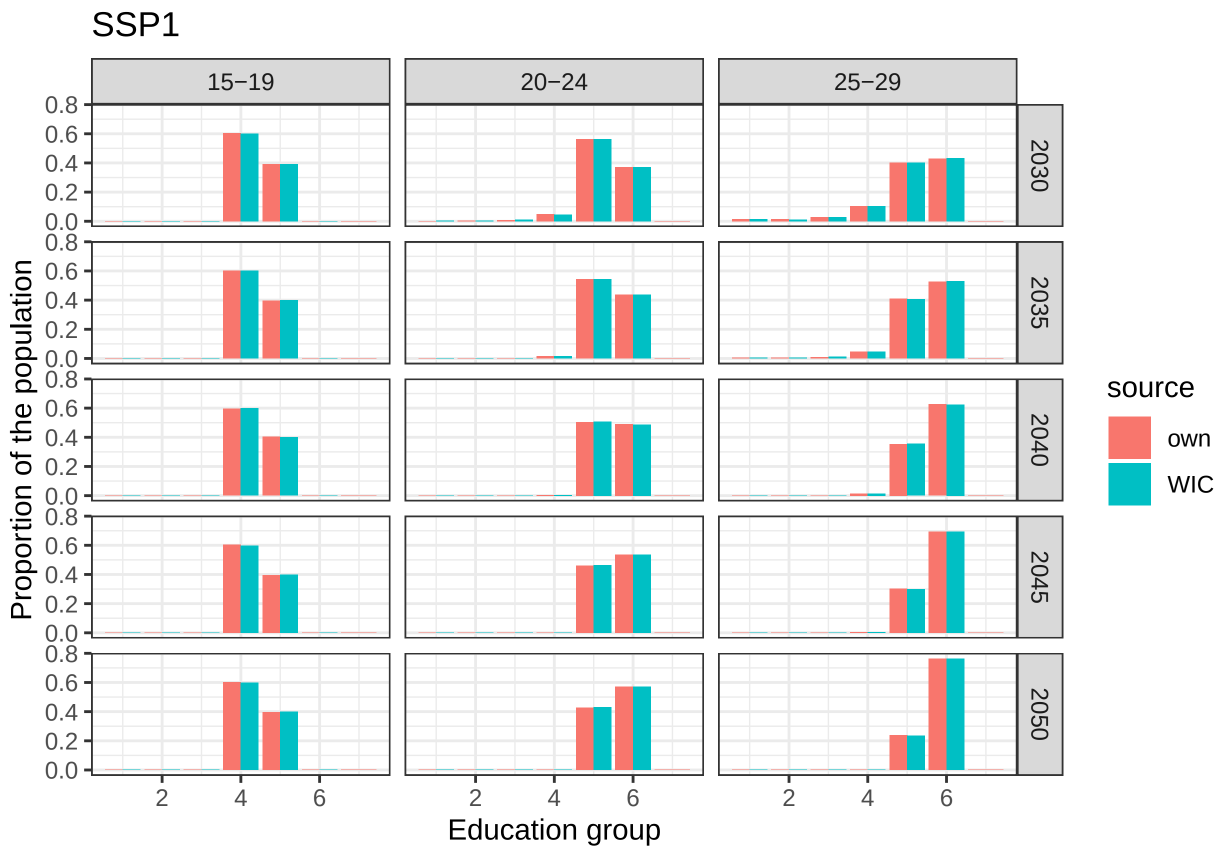

Figure 3: Proportion of the population in three age categories from 2030 to 2050 in the microsimulation, compared with WIC data, for SSP1 scenario.

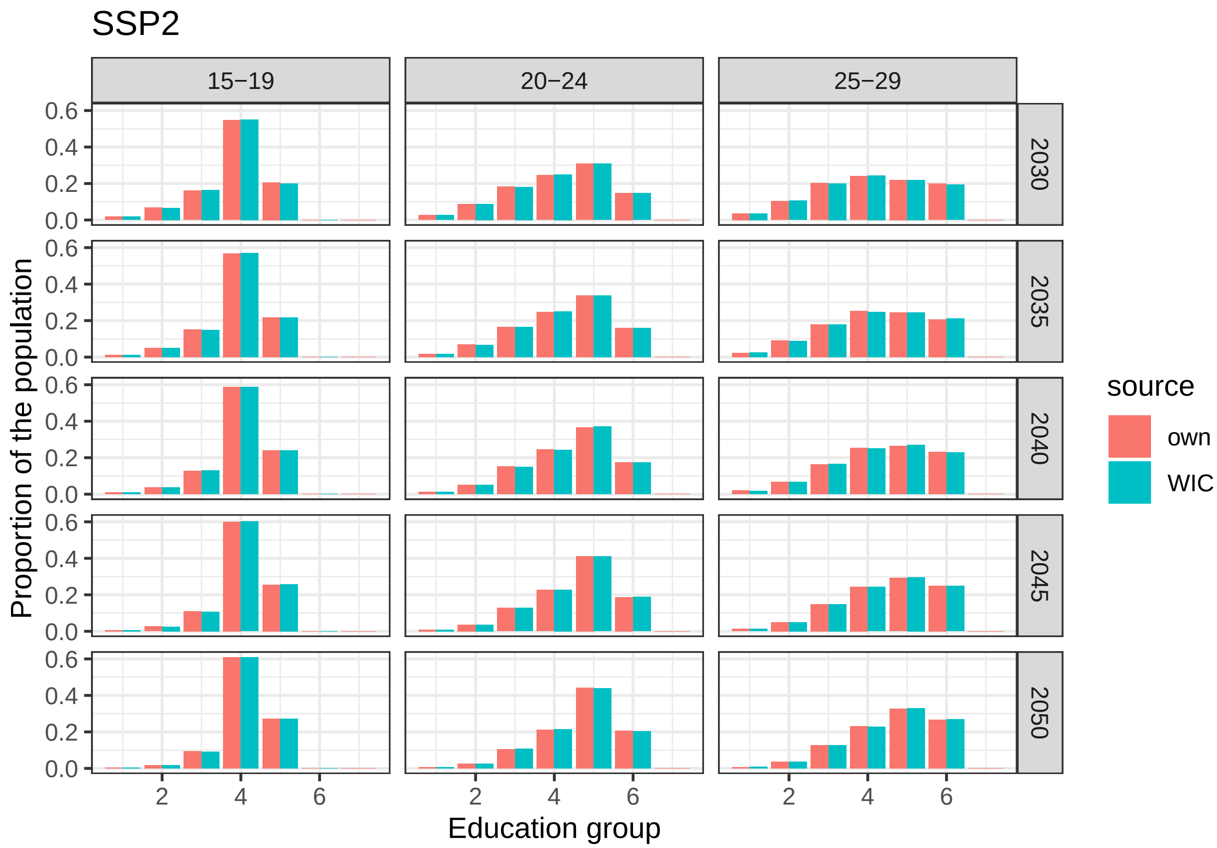

Figure 4: Proportion of the population in three age categories from 2030 to 2050 in the microsimulation, compared with WIC data, for SSP2 scenario.

92 **Supplementary Figure 5: Validation of the microsimulation model**

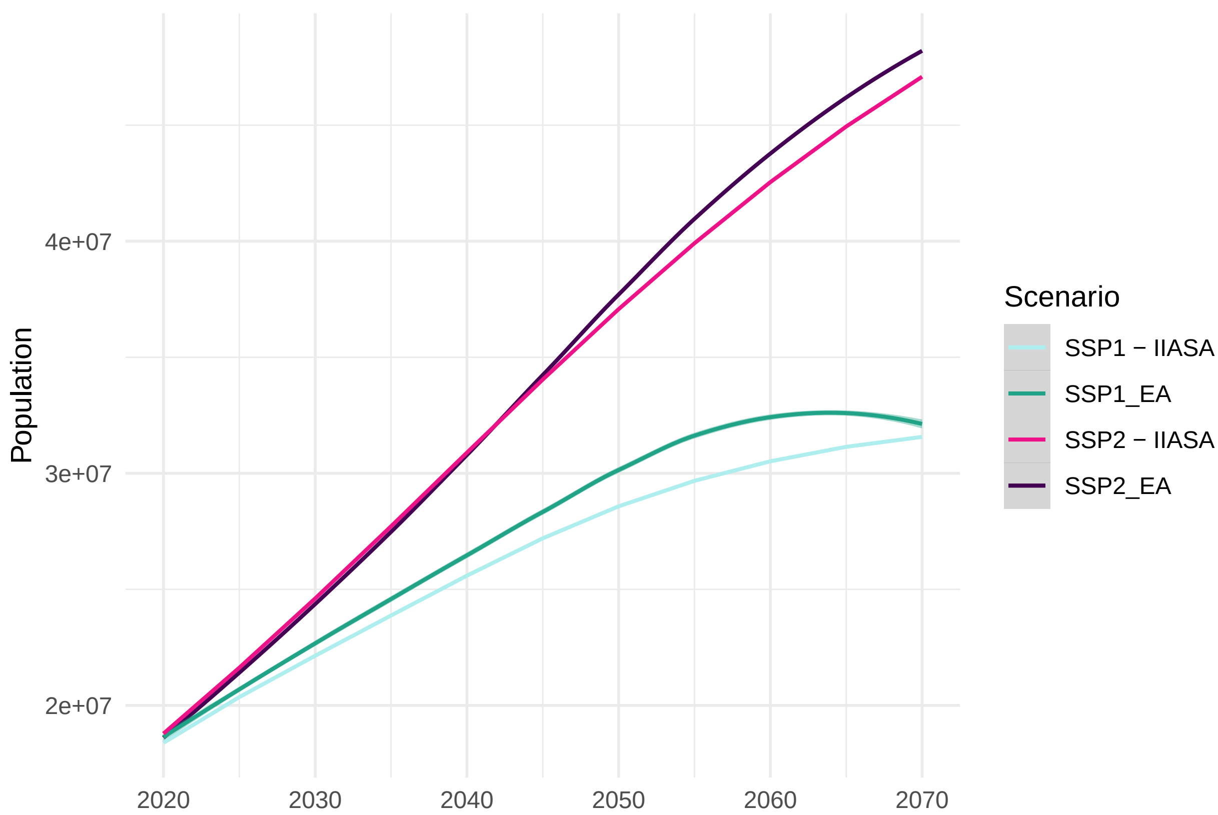

Figure 5: Population pathways from a simulation of the microsimulation model in which the fertility module was replaced by Age-Specific Fertility Rates projections from WIC data, compared with population pathways from the WIC data, for SSP1 and SSP2.

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