Investigating and modelling endogenous socio-economic dynamics in long-term electricity demand forecasts for rural contexts of developing countries

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Acknowledgment to:
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Elias Hartvigsson (Chalmers University of Technology

The research NEED
research CONTEXT

The global dimension of access to electricity issue in remote areas of DCs:

2030

At least 2.5 billions to be electrified (today deficit plus the projected population growth)

*The IEA and the WB - Global Tracking Framework Report 2015

The need of sustainable electricity planning approaches

The research NEED
research PROBLEM

How to project electricity needs and consumption patterns within long-term off-grid electricity planning

Electricity consumption is forecasted to grow fast in developing contexts, **ESPECIALLY IN RURAL CONTEXTS**

High uncertainty

↓

Unreliable predictions

↓ *~~On~~- Off-grid*

Unreliable system design

SIZING

ELECTRIC CONTROL and REGULATION

BUSINESS PLANS and TARIFFS definition

The research NEED
research THEME

Specific Objectives:

1. to **identify** and **conceptualise** the local dimension of electricity demand and socio-economic development nexus

2. to **develop** a **simulation model** able to generate projections of electricity demand for unelectrified contexts

Value added (General objectives):

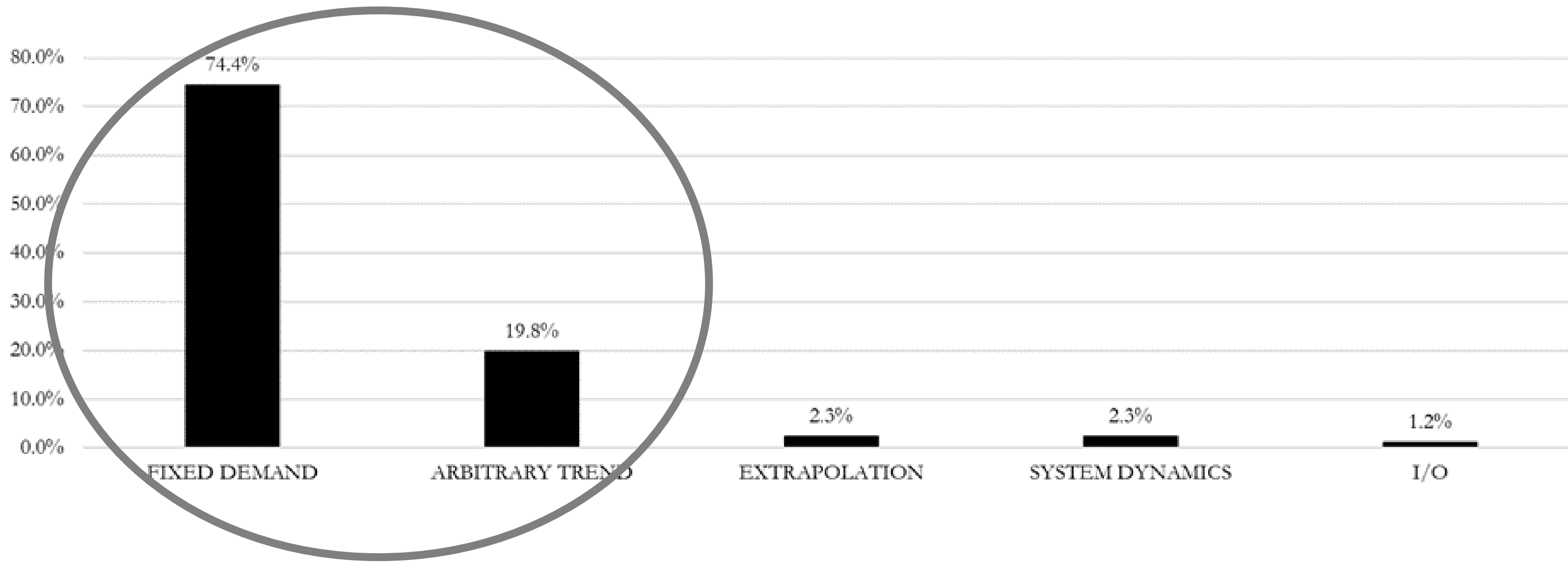
- To **contribute** to the cutting-edge research committed to develop **appropriate, reliable and robust Rural Electricity Plans** for off-grid areas of the world

- To **support** NGOs, private companies, and public utilities in the **engineering design** and **investment plans** for reliable off-grid power systems

State of the art

"existing solutions can't"

Current models adopted in the literature for rural energy demand

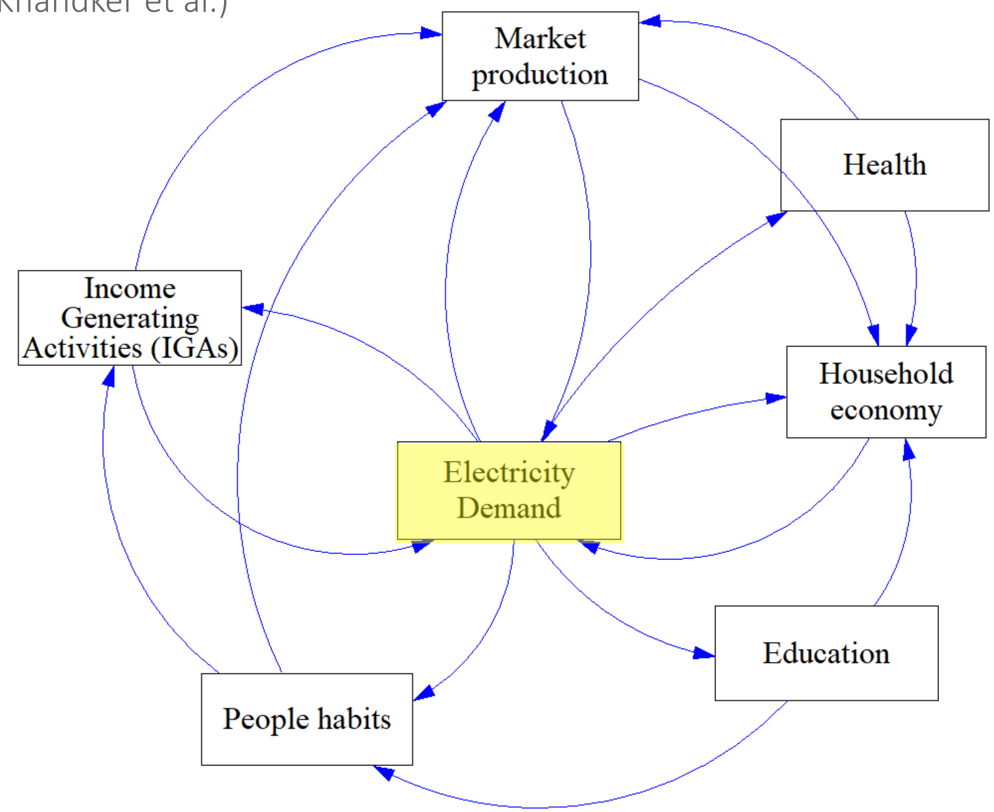


- **74.4 %** of the studies considers a **constant energy demand** along the overall life cycle
- **19.8 %** of the studies estimates an **exogenous constant annual rate of growth** of the demand based on past experience, monitored data, national trends, assumptions

***Riva, F.,** Tognollo, A., Gardumi, F., & Colombo, E. (2018). Long-term energy planning and demand forecast in remote areas of developing countries: Classification of case studies and insights from a modelling perspective. *Energy Strategy Reviews, 20, 71-89. DOI: 10.1016/j.esr.2018.02.006.*

State of the art
the way-forward: why SD?

“the dynamics of growth and electrification are complex, involving many [endogenous] underlying forces” (Khandker et al.)



COMPLEX ISSUE

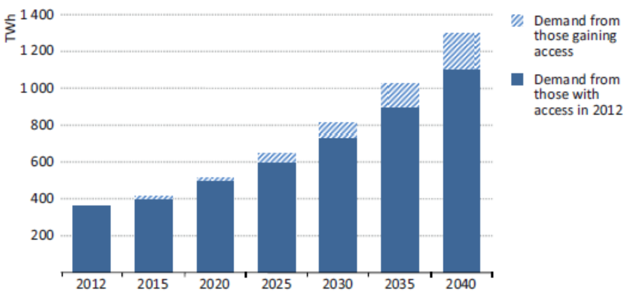
Towards mathematical instruments able to tackle such techno-economic and social complex dynamics:
SYSTEM DYNAMICS

≠ *COMPLICATED* ISSUE

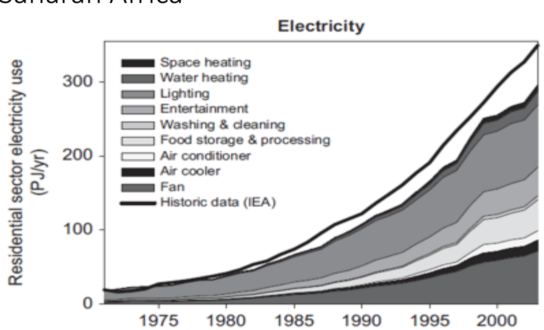
SD model development

- MODEL PURPOSE: ***to investigate*** *the local socio-economic complexities* of the electricity-development nexus and ***generate*** *long-term projections of electricity demand* for rural contexts of developing countries

- Literature-based **reference modes** for long-term **electricity demand** in developing contexts:

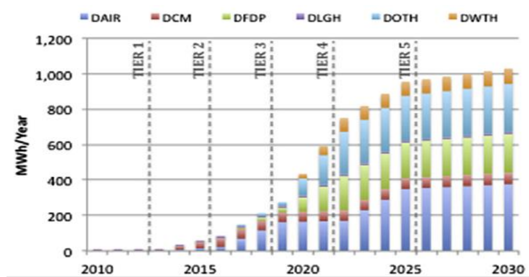


IEA, 2015 → electricity demand in sub-Saharan Africa

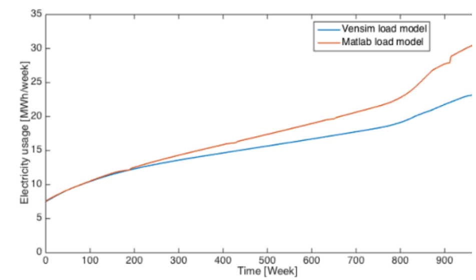


B. Ruijven, 2011 → household electricity demand in India

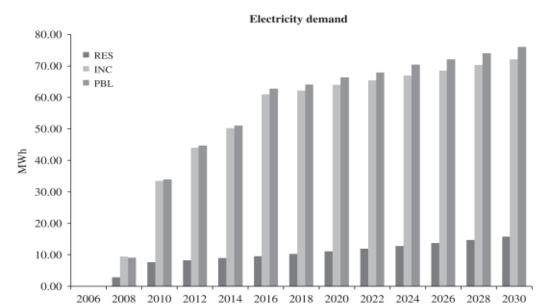
N A T I O N A L



F. Nerini, 2015 → energy demand growth in a village in Timor Leste



E. Hartvigsson, 2016 → electricity load in rural Tanzania



S. Mustonen, 2010 → electricity growth paths for a rural village in Laos

RURAL

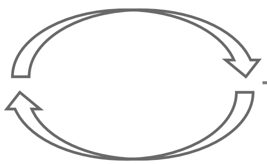
SD model development

- **Feedback loops** of the system:

Review of the local dimension of electricity-development nexus:

6 main dynamics identified:

Electricity demand



- i. income generating activities
- ii. market production
- iii. household economy

ECONOMIC

- iv. education
- v. people habits
- vi. health

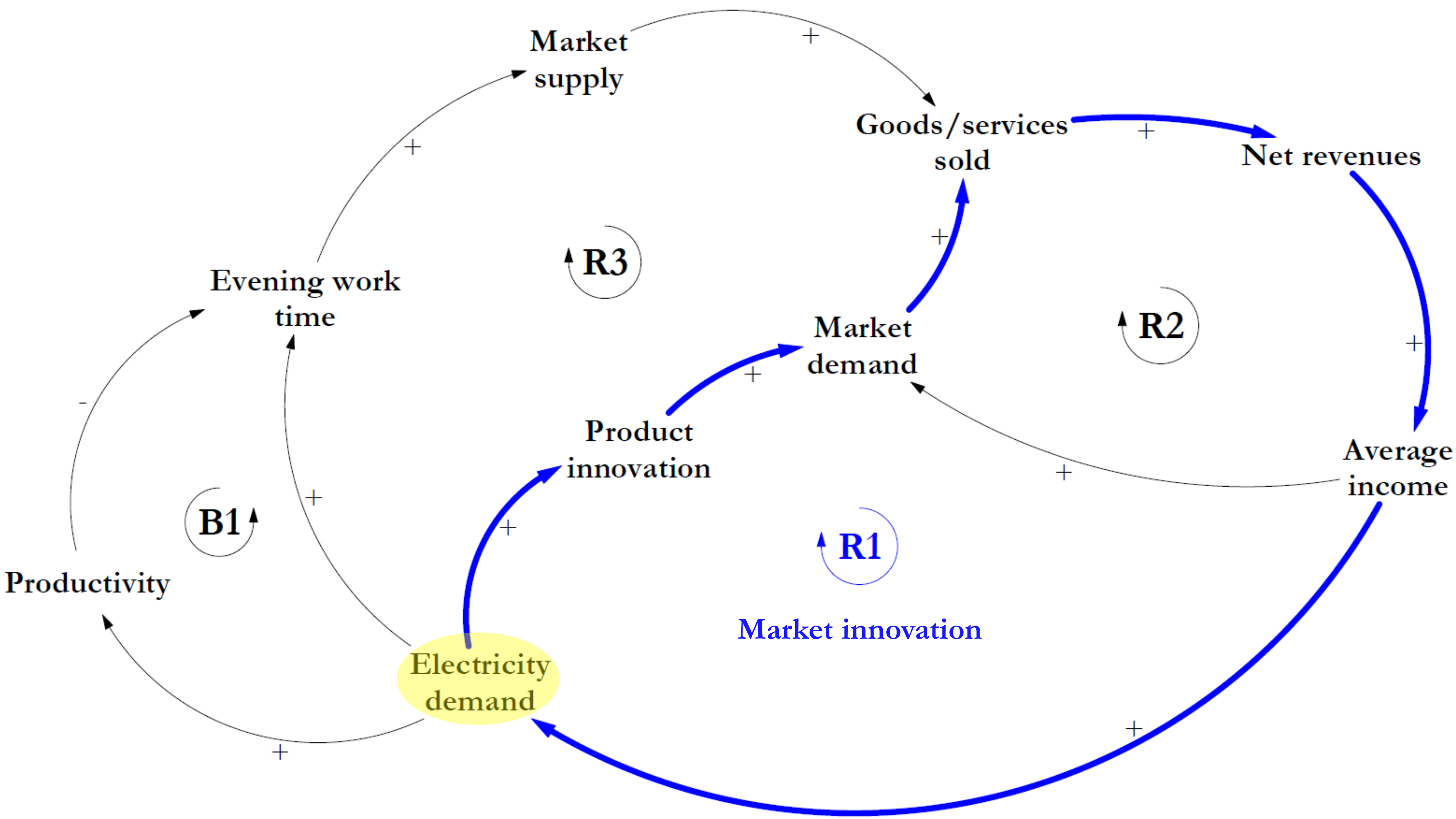
SOCIAL

* **Riva, F.**, Ahlborg, H., Hartvigsson, E., Pachauri, S., & Colombo, E. (2018). Electricity access and rural development: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling. *Energy for Sustainable Development, 43, 203-223. DOI: 10.1016/j.esd.2018.02.003*

SD model development

1) Conceptualisation

e.g. electricity demand ←→ Market production *dynamics*



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SD model development

1) Conceptualisation

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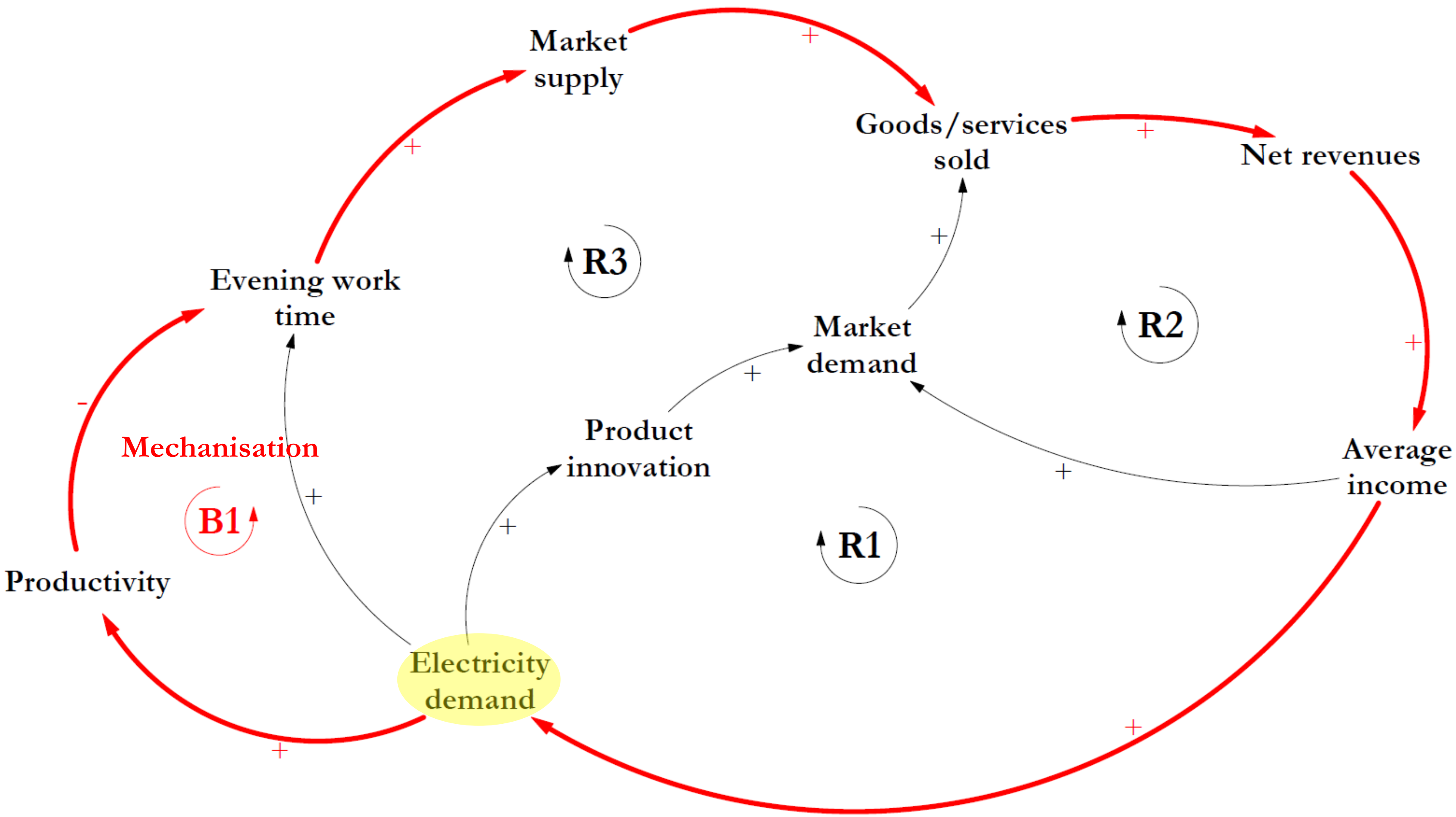

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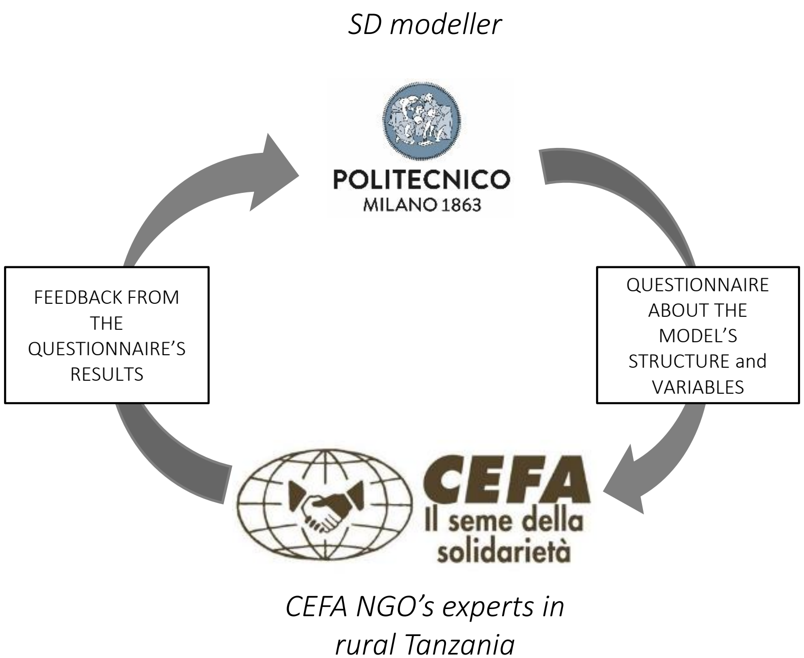
SD model development

- Converting *feedback diagrams to **level/stocks** and **rate/flows equations***



DSS

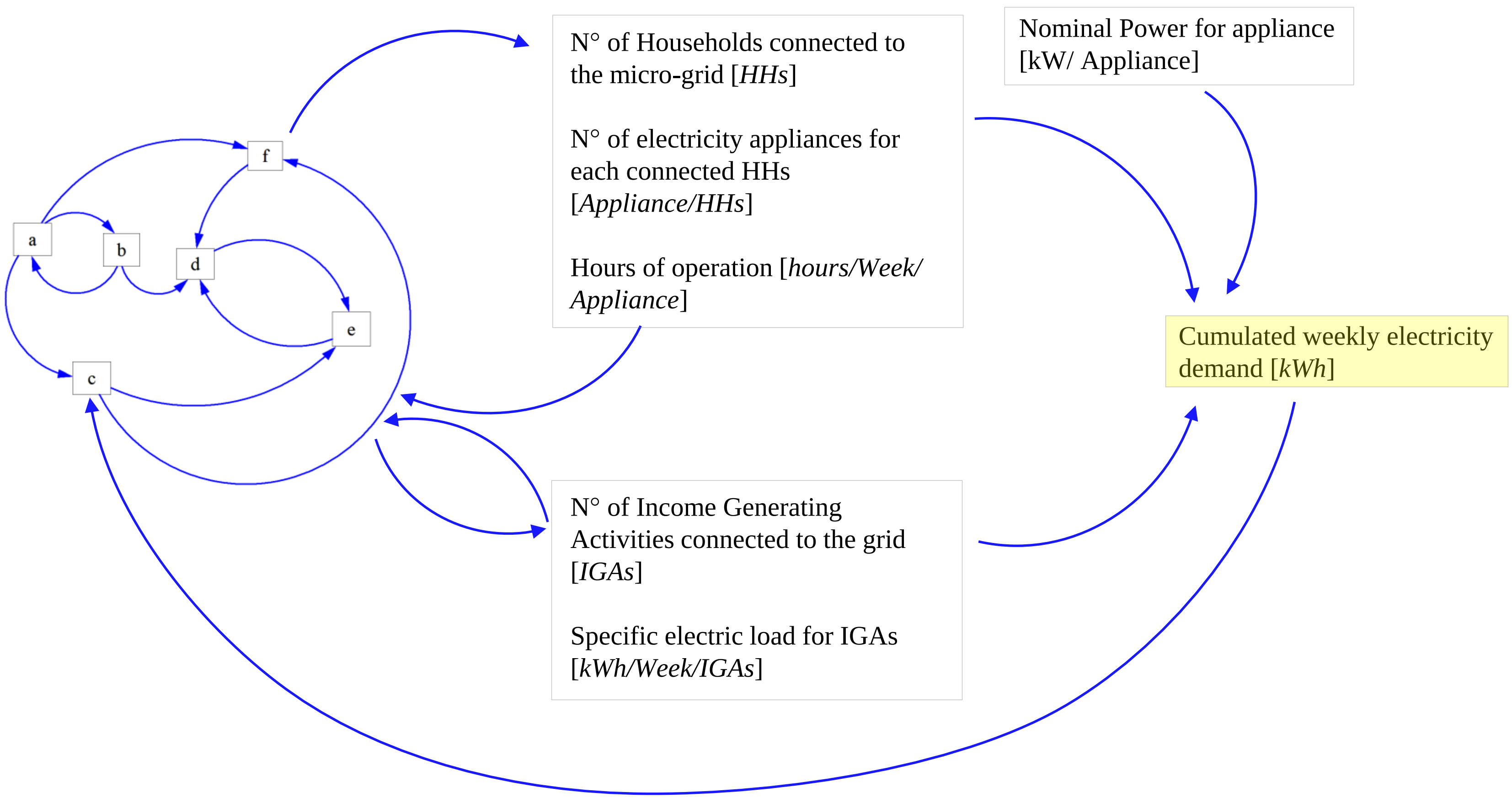
THE MODEL

100 levels
333 auxiliary variables
153 constants
8 look-up tables

time-step = **0.25 week**
Euler integration

SD model development

For each time-step *dt* of the chosen simulating horizon (e.g. 20 years), the model generates values of electricity demand for a typical rural community.



SD model development

- Estimation of **parameters**:

a) Interviews in Ikondo – Matembwe, Tanzania

- Village of around 4000 people and **800 households (HHs)**
- 100-120 income generating activities (**IGAs**)
- **Agriculture**-based livelihood

- **Hydroelectric plant** of about 400 kW
- installed in **2005** by **CEFA** NGO
- **previously, no access** to electricity in the village
- managed by the local utility MVC

- **18 interviews** to:
  - MVC's and CEFA's **experts**
  - local **farmers**
  - local **people involved in an IGA**

AIM:
- to define a realistic range for some ***auxiliary variables***
- to define a calibration range for ***constants***

SD model development

- Estimation of **parameters**:

b) Model calibration

DATA

Historical time series (2005-2017) of **Ikondo's plant data**:

1. **Connections** of IGAs
2. **Connections** of HHs
3. **Monthly electricity consumption** of IGAs
4. **Monthly electricity consumption** of HHs

TOT: 517 data points

Optimisation control

- **115** parameters
- **Parameter spaces** taken from the **interview** and the **literature**
- Powell optimiser of Vensim DSS
- 4 payoff definitions for 4 *calibration variables*

SD model development

3) Testing and Validation
according to model purpose

*Y. Barlas, 1996
*J. D. Sterman, 2000

1  +1  = ?

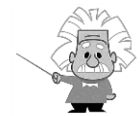
direct structure
tests

- **Boundary Adequacy:**


INTERVIEWS
in IKONDO

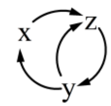

LITERATURE

- **Structure Assessment:**


CEFA'S LOCAL
EXPERTS


GROUP MODELLING
AT POLITECNICO

- **Dimensional Consistency:**

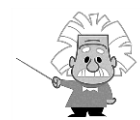


VENSIM UNIT
CHECK

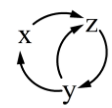
EQUATIONS
INSPECTION

- **Parameter Assessment:**


INTERVIEWS
in IKONDO


CEFA'S LOCAL
EXPERTS

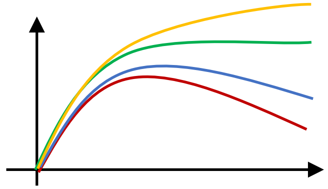

PLANT'S DATA



VENSIM
CALIBRATION

SD model development

*Y. Barlas, 1996
*J. D. Sterman, 2000



structure-oriented behaviour tests

- Extreme conditions: VENSIM REALITY CHECK, VENSIM SyntheSim

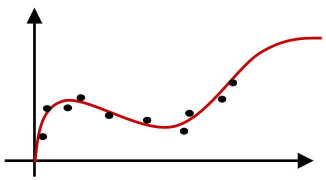
- Integration Error:
  - LITERATURE: $\boldsymbol{dt} \leq$ ¼ the size of the smallest time constant (i.e. 1 week)
  - VENSIM TRIALS:

$$\boldsymbol{dt}\ s.t.\ \frac{\boldsymbol{x}(t = FINAL, dt) - x\left(t = FINAL, \frac{dt}{2}\right)}{x(t = FINAL, dt)} \leq 2.5\%$$

$\forall\ \boldsymbol{x}$ calibrated variable

SD model development

*Y. Barlas, 1996
*J. D. Sterman, 2000



behaviour pattern
tests

→ Behaviour Reproduction:

INTERVIEWS in IKONDO

CEFA'S LOCAL EXPERTS

THEIL ANALYSIS in VENSIM

for $\boldsymbol{n} = \mathbf{25}$ variables:

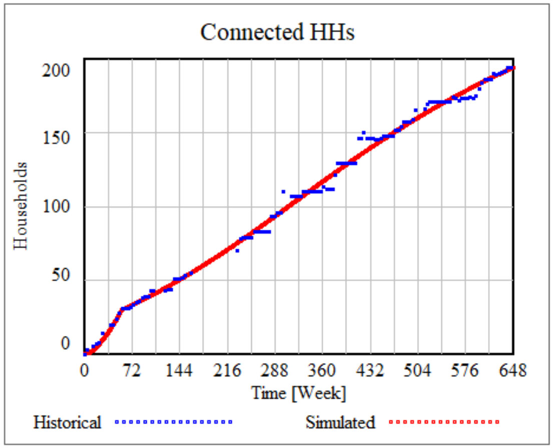
$$\boldsymbol{x_n}(t = FINAL) \in [\bar{x}_{n,min} - \bar{x}_{n,max}] \quad \forall \boldsymbol{n}$$

with $\bar{x}_{n,min}$, $\bar{x}_{n,max}$ *the* $\boldsymbol{min}$ *and* $\boldsymbol{max}$ *values for* $\boldsymbol{x_n}$ *gathered during the local interviews*

SD model development

3) Testing and Validation according to model purpose

Theil analysis

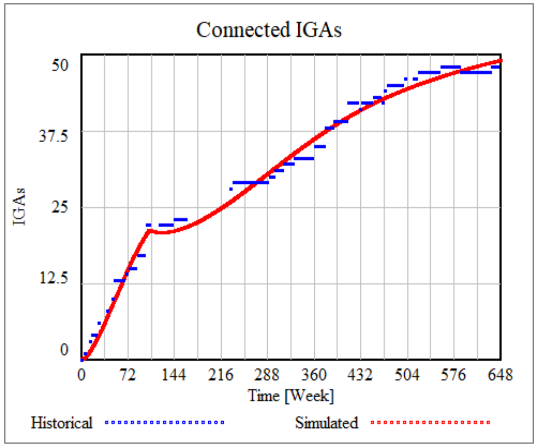


MAPE = 3.70%

U^M= 1.96%

U^S= 0.22%

U^C= 97.82%

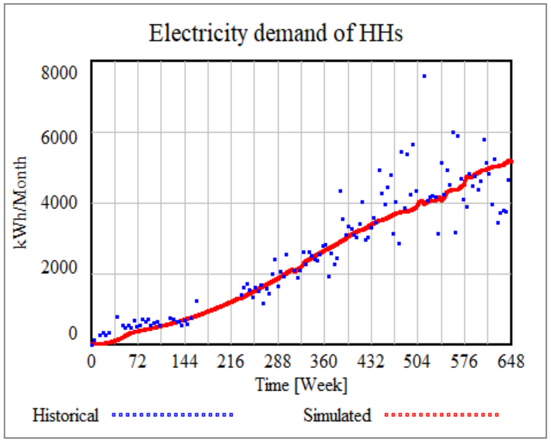


MAPE = 5.36%

U^M= 0.23%

U^S= 0.08%

U^C= 99.69%

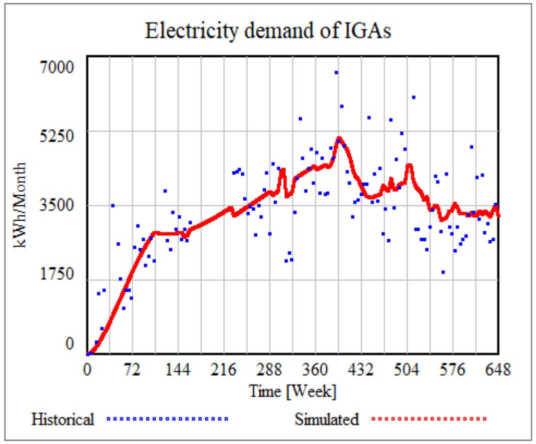


MAPE =20.58%

U^M= 0.48%

U^S= 0.00%

U^C= 99.52%



MAPE = 19.22%

U^M= 2.87%

U^S= 0.48%

U^C= 96.65%

$U^M < 3\%$ Very low bias in the *mean*

$U^M \sim 0$ Model and data show the same *trends*

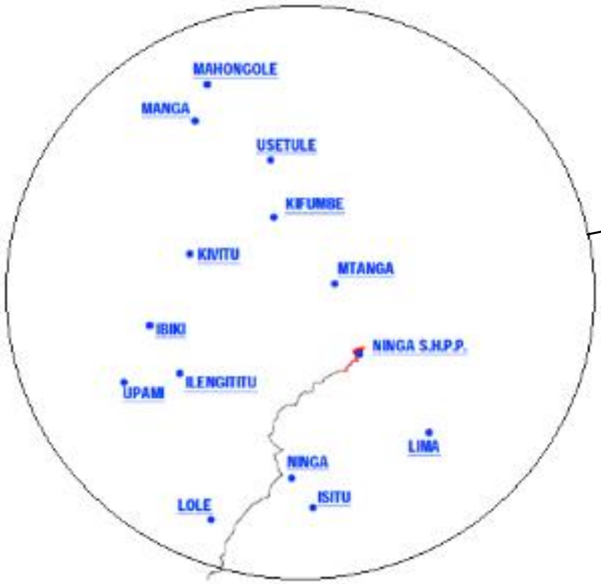
$U^C \rightarrow 1$ Model tracks actual data except for a random error term with zero mean
Unsystematic error since the purpose of the model is not to study the cycles in the data

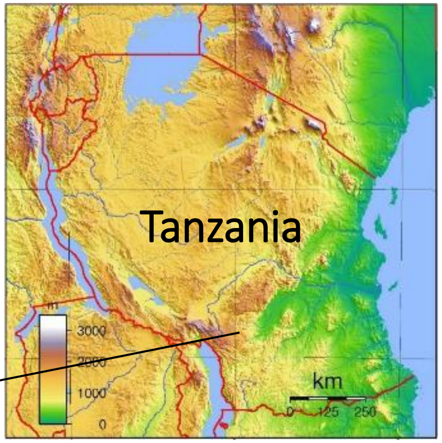
Future activities

- **Sensitivity analysis** and test of the model's response to different policies

- **Application to a future CEFA's project** of a Small Hydro Power Plant (SHPP):

13 villages to electrify
(about 5'600 HHs and 350 IGAs)





Technical features of the future Ninga-SHPP power plan

Intake location	UTM 725.465 E; 9.001.143 N 1397.50 m asl
Powerhouse location	UTM 725.167 E; 9.001.159 N 1322.24 m asl
Penstock length	177.5 m
Gross head	76 m
Mechanical capacity	6.3 MW
Electrical power	6.0 MW
Annual energy output	26,410,000 kWh

Future activities

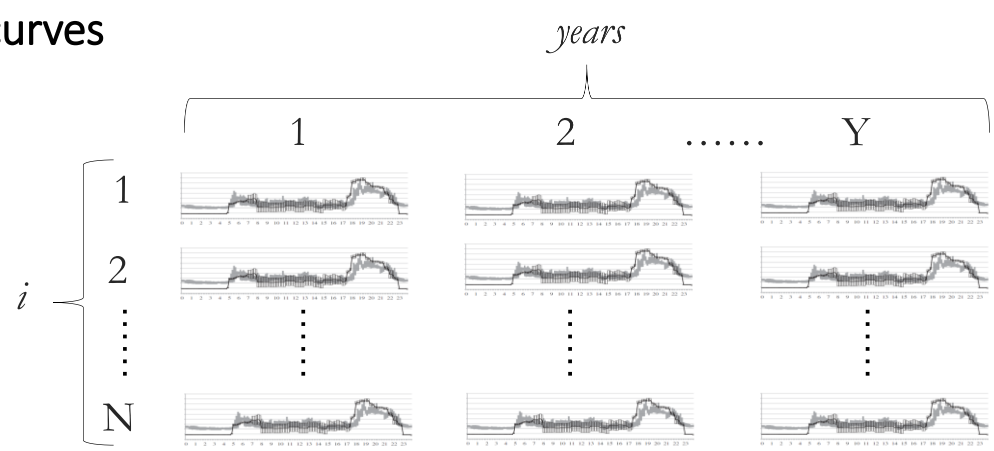
- **Application to a future CEFA's project of a Small Hydro Power Plant (SHPP):**

1. Generating ***N* Monte Carlo samples** for the M (=115) parameters calibrated during formulation → N combinations of the M parameters

2. **SD model simulation**

```
for i=1,..., N
     SD_i model  →  diffusion of el. connections_i and el. appliances_i
end
```

3. Derivation of the long-term **load curves**



4. **Stochastic design** and **size** of the SHPP, according to the simulated load curves

Conclusion

- Electricity demand is **growing fast** in remote areas of developing countries

- **Reliable predictions** are mandatory in order to make sustainable local electricity plans

- The evolution of electricity demand is a ***complex* problem**

- I demonstrated that **SD** is a **viable and reliable modelling approach** to investigate this issue, by developing a bottom-up model through the main phases of the modelling process:
  - *Conceptualisation*
  - *Formulation*
  - *Testing*

- Future work will consider the implementation of the model to a Small Hydro Power Plant project in rural Tanzania

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thank you

4 your kind attention