Sustainability of local manufacture and local maintenance of small wind turbines in remote areas

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167th EAAE Seminar and Conference on Bioeconomy

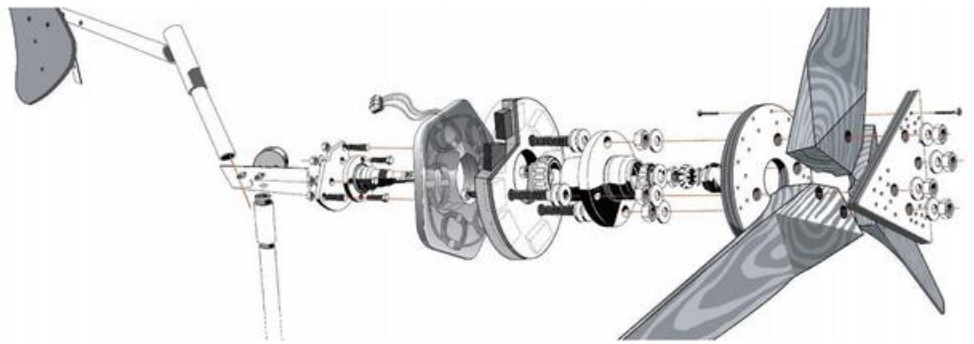
24 September 2018

Diverging visions of Bioeconomy

- **Bio-technology** oriented
- Advancement of agricultural and industrial biotechnologies
- "Green growth"
- Industrial perspective
- Technological progress
- Closely tied to the agenda of Life sciences and Biotech industry

- **Agroecology** oriented
- Low external input agricultural practices resulting in shorter supply chains
- Joint production of food, biomass and renewable energy on-farm
- Comprehensive sustainability - systemic changes
- Advocates sharing of knowledge, participatory governance and a sufficiency perspective

Locally Manufactured Small Wind Turbines (LMSWTs)



- Renewable energy
- Small-scale
- Local materials and resources
- Supportive to local economy
- Socially embedded
- Based on the Open sharing of knowledge

- Development component of the agroecological vision
- Combined with other renewable sources for on-farm energy generation

Locally Manufactured Small Wind Turbines (LMSWTs)

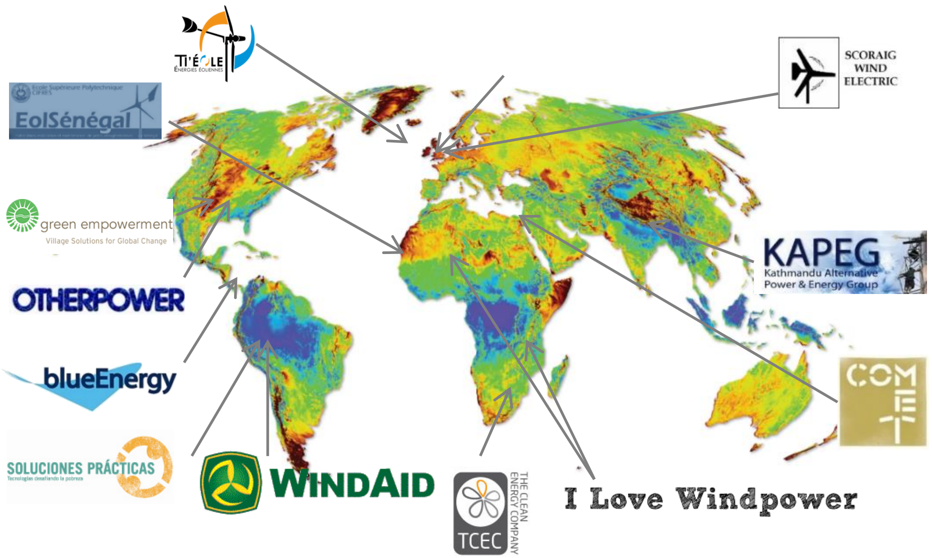
Locally Manufactured:

- Manufactured/installed/maintained by non-experts
- Simple tools/techniques/facilities
- Mostly locally-sourced materials

Small:

- Rotor diameters: $1.2 - 7m$, Rated power: $0.2 - 4kW$

- Hugh Piggott - "A Wind Turbine Recipe Book"
- Open design – not patented
- Global community – Bottom up innovation
- Wind Empowerment association



Small Wind Turbines for rural applications

- Off-grid, rural areas with sufficient wind resource
- Complementary with other renewable sources
- Wind energy traditionally used for water pumping and grain milling
- More recently for aquaponics, processing food, refrigeration of products

- Commercial Small Wind Turbines
  - High capital cost
  - High maintenance requirements
  - Not reliable - Externally dependent lifecycle

- Locally Manufactured Small Wind Turbines
  - Significantly lower capital cost
  - Can support the creation of a local maintenance network

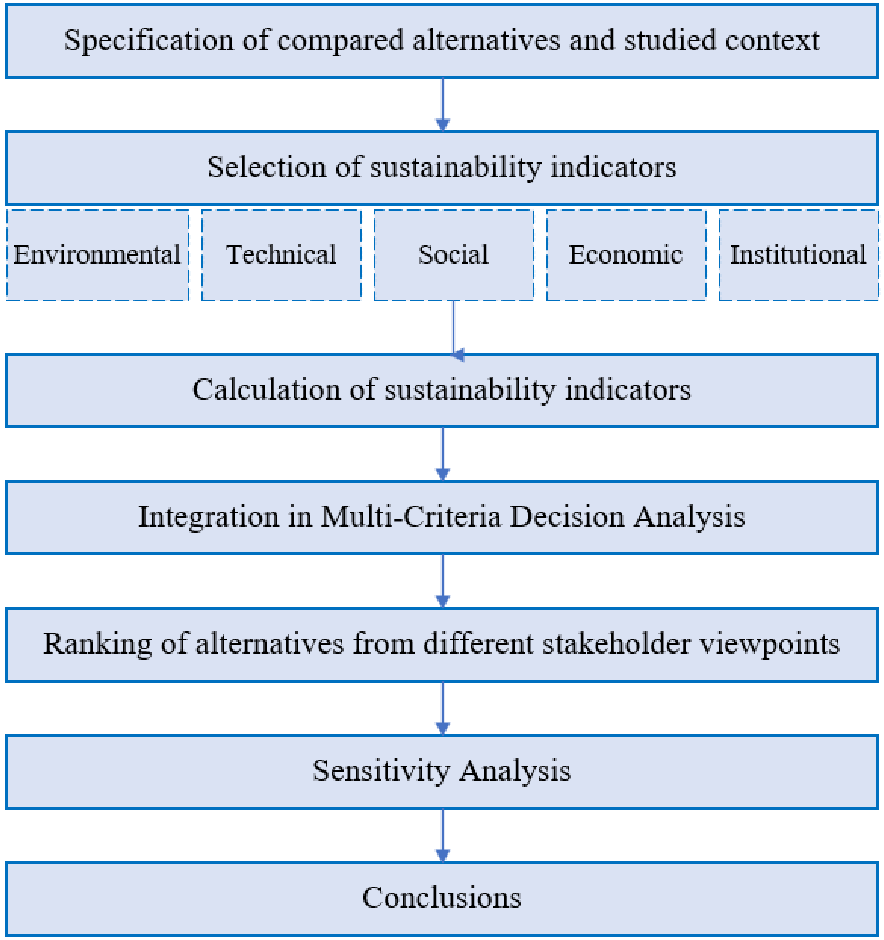
*This alternative model of **local manufacture and local maintenance** creates the potential to rebuild the reputation of **SWTs as a sustainable component for rural electrification***

Objective

To assess how local manufacture and local maintenance affects the life cycle sustainability of small wind turbines in remote areas.

Methodology

- ➢Specification of context and compared alternatives
- ➢Selection of sustainability indicators
- ➢Calculation of sustainability indicators
- ➢Integration in Multi-Criteria Decision Analysis (MCDA)
- ➢Ranking of alternatives from different stakeholder viewpoints
- ➢Sensitivity Analysis
- ➢Conclusions



Specification of context

Case study: Electrification of rural community in Ethiopia

- 2015: Rural electrification project in Ethiopia
- A 3m wind turbine was locally manufactured and installed along with solar panels to electrify a rural shop
- Manufactured at the Jijiga Polytechnic College (15km from site)
- 7-day Training course – 22 participants
- Maintenance conducted locally with the support of the college

Jijiga - Jan 2015

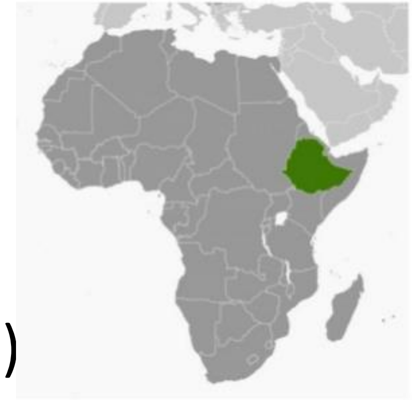
Specification of context

Case study: Electrification of rural community in Ethiopia

- **Location**: Handew, Somali region, Ethiopia
- 15km from Jijiga, 140km from Dire Dawa, 600km from Addis Ababa

- **Mean Wind Speed**: 3.12 m/s

- **Load**: 1.2kWh daily (fridge, lights, mobile phone charging)



Jijiga - Jan 2015

Specification of compared alternatives

Compared wind turbines		
Wind turbine	**LM 3m**	**Bergey XL.1**
Wind turbine topology	3-blade, Horizontal Axis Wind Turbine (HAWT)	
Generator topology	Axial flux permanent magnet	Radial flux permanent magnet
Rotor diameter (m)	3	2.5
Rated power (W) (at 11 m/s)	900	1000
Annual yield (at 3.12 m/s, 12m) (kWh)	630	470
Lifetime of moving parts (years)	20	20
Lifetime of fixed parts (years)	30	30

- Dire Dawa (DD), a city located **140km** from Handew
- Addis Ababa (AA), the capital of Ethiopia located **600km** from Handew

- **Delivery Model 1 (DM1)** comprises local manufacture and provision of training to local people in nearby town (**15km**), so that maintenance can occur locally.
- **Delivery Model 2 (DM2)** comprises local manufacture with no training provided, so that maintenance services are provided by a SWT business within Ethiopia (**140 or 600km**).
- **Delivery Model - Conventional (DM-C)** comprises import of a commercial, mass-produced SWT and maintenance services provided by a SWT business within Ethiopia (**140 or 600km**), with spare parts imported on demand from the manufacturer.

Compared alternatives

A1) LM 3m, DM1: Local manufacture, Training provided and Local maintenance in Jijiga (15km)

A2) LM 3m, DM2, DD: Local manufacture, External support for maintenance from SWT business in Dire Dawa (140km)

A3) LM 3m, DM2, AA: Local manufacture, External support for maintenance from SWT business in Addis Ababa (600km)

A4) Commercial, DM-C, DD: Imported wind turbine, External support for maintenance from Dire Dawa (140km) and Imported spare parts

A5) Commercial, DM-C, AA: Imported wind turbine, External support for maintenance from Addis Ababa (600km) and Imported spare parts

Compared alternatives

Basic parameters

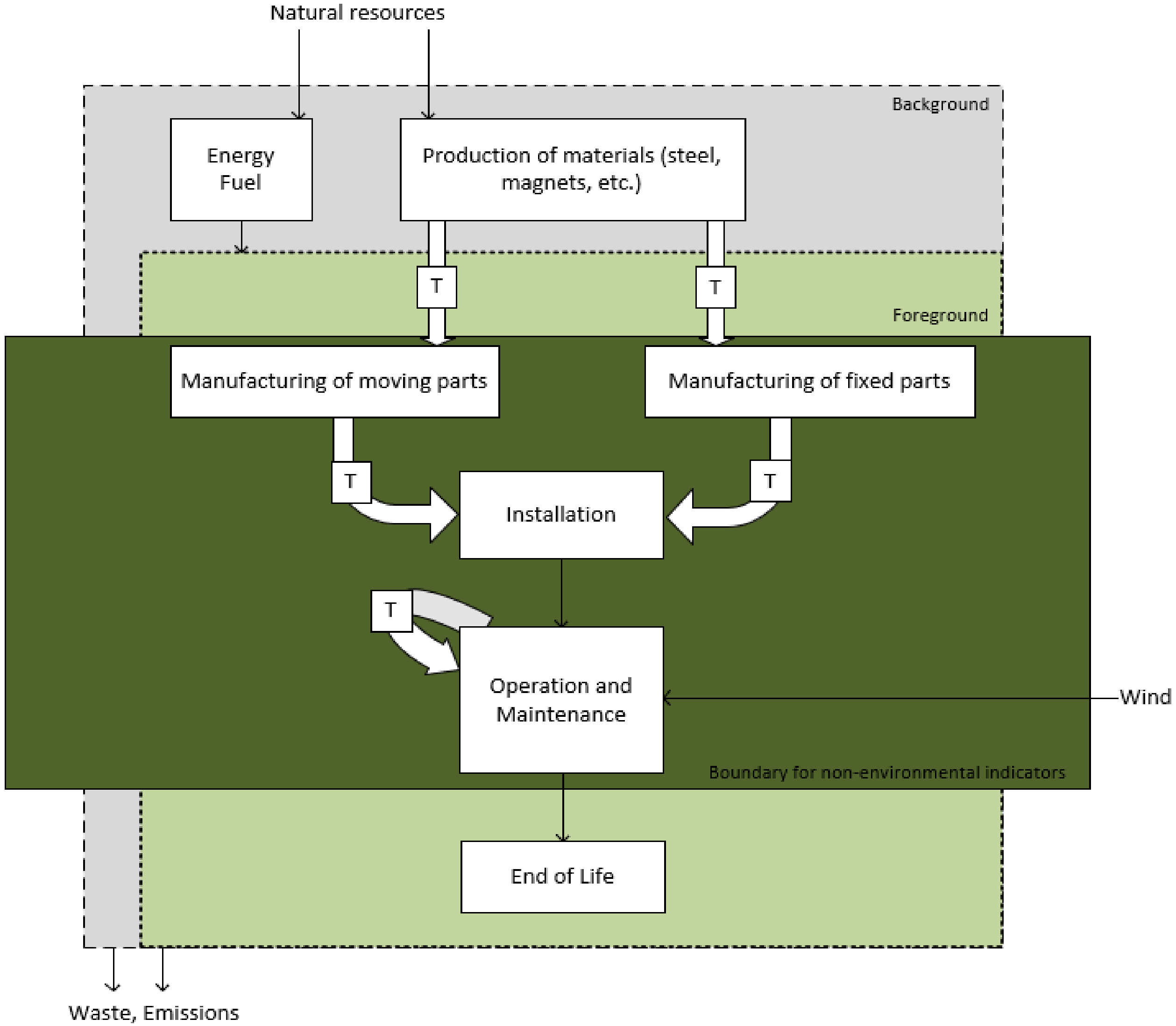
#	**Alternatives**	Frequency of maintenance activities (times/lifetime)	Lifetime distance covered for maintenance (km)	Downtime (days)	Lifetime electricity generation (kWh)
A1	**LM3m, DM1, DD**	20	600	3	12496.4
A2	**LM3m, DM2, DD**	20	5600	15	12082.2
A3	**LM3m, DM2, AA**	20	24000	30	11564.4
A4	**Commercial, DM-C, DD**	10	2800	30	9013.7
A5	**Commercial, DM-C, AA**	10	12000	45	8820.5

Selection of sustainability indicators

Category	*Sustainability issue*	*Indicator*	*Unit*
Environmental	Fossil energy resources depletion	1. Non-renewable primary energy	MJ/kWh
	Global warming	2. Global warming	gCO_{2eq}/kWh
	Use of abiotic resources (elements)	3. Metal depletion	gFe_{eq}/kWh
Technical	Operability	4. Availability factor	%
Economic	Investment cost	5. Initial investment	€
	Operating cost	6. Annual O&M costs	€/year
	Levelized cost of generation	7. LGC	€/kWh
Institutional	Institutional support	8. Institutional cost	Qualitative
Social	Provision of local employment	9. Local to national labour	%
	Support of national economy	10. National to total expenses	%

Calculation of sustainability indicators

Methods and data acquisition



Environmental indicators

✓Life Cycle Assessment

- ISO 14040/14044, SimaPro software
- From cradle-to-grave

All other indicators

✓Lifecycle approach followed – with limitations

- End-of-Life and Background processes not considered
- Assessment within the borders of the country of installation

Data sources

- Rural electrification project in Ethiopia
- Wind Empowerment network
- Literature

Calculation of sustainability indicators

Environmental indicators

- ***Non-renewable primary energy (MJ/kWh)***
- ***Global Warming Potential (g_{CO2eq}/kWh)***
- ***Metal depletion (g_{Feeq}/kWh)***

Technical indicator

- ***Availability (%)***: The percentage of time the small wind turbine is available to produce electricity

$$Availability\ (\%) = \frac{(365\ days\ per\ year) - (Downtime\ days\ per\ year)}{(365\ days\ per\ year)} * 100\%$$

Calculation of sustainability indicators

Economic indicators

- ***Initial investment (€):*** All capital required for the system to start operating
  - *LMSWT*: Material and labour costs during Manufacturing, Installation and Training stages
  - *Commercial*: The sum of the retail price, the delivery cost and the installation cost.
- ***Annual O&M costs (€/year)****:* The annual cost of materials, labour and transportation for performing maintenance
- ***Levelized Generating Cost (€/kWh)****:* The ratio of total costs of generation to the total electricity generated during the lifetime of the wind turbine, taking into account an appropriate discounting factor.

$$LGC = \frac{I + \sum_0^N \frac{AC_t}{(1+r)^t}}{\sum_1^N \frac{E_t}{(1+r)^t}} \qquad (€/_{kWh})$$

I – Initial investment (€)
AC_t – Annual O&M costs in year t (€)
E_t – Electricity generation in year t (kWh)
r – Discount rate
N – Lifetime of the wind turbine (moving parts)

Calculation of sustainability indicators

Social indicators

- ***National to total expenses rate (%)***: Reflects the percentage of wealth that stays within the national economy. Calculated as the percentage of all expenses made at national level over the total expenses throughout the system's lifecycle.

$$National\ to\ total\ expenses = \frac{Expenses\ at\ national\ level}{Total\ expenses} \times 100\%$$

- ***Local to national labour rate (%)***: Reflects provision of employment in remote areas. Calculated as the percentage of labour* offered locally near the site over total national labour*.

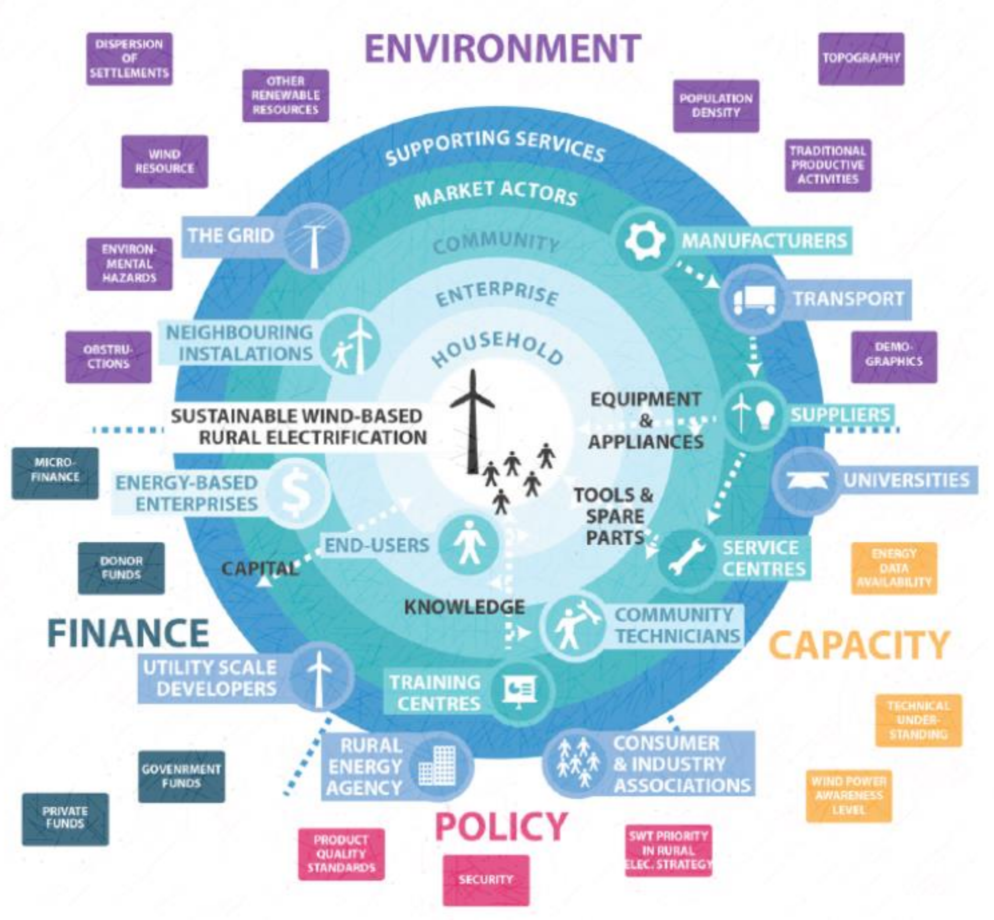
$$Local\ to\ national\ labour = \frac{Local\ labour}{Total\ national\ labour} \times 100\%$$

* Labour (measured in persondays) refers to preventive and corrective maintenance, as well as travel days.

Calculation of sustainability indicators

Institutional indicator

- ***Institutional burden (Qualitative):***
  - Reflects the institutional cost for employing each alternative
  - Comprises generic cost to issue policies, establish infrastructure, supportive network and local capacity
  - On a scale of 1 (minimum) to 5 (maximum burden)
  - Assumed local manufacture and provision of training for local maintenance induces higher institutional burden



The small wind turbine ecosystem, adapted from [practical action 2012] by Sumanik-Leary et al. 2013

Performance of alternatives

	Indicators	Technical	Economic [1]			Environmental			Social		Institutional
		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Criterion 10
#	Alternative	Availability	Initial investment (€)	Annual O&M costs (€/year)	Levelized Generating Cost [2] (€/kWh)	Non-renewable primary energy (MJ/kWh)	Global Warming (gCO_{2eq}/ kWh)	Metal depletion (gFe_{eq}/ kWh)	Local to national labour rate	National to total expenses rate	Institutional burden
A1	LM3m, DM1	0.992	3207	148	0.75	1.68	136.424	41.178	0.289	0.937	5
A2	LM3m, DM2, DD	0.959	2632	197	0.76	3.766	278.762	56.671	0	0.941	4
A3	LM3m, DM2, AA	0.918	2828	392	1.16	11.735	820.713	113.351	0	0.963	4
A4	Commercial, DM-C, DD	0.959	5801	131	1.59	2.955	232.862	63.495	0	0.27	1
A5	Commercial, DM-C, AA	0.938	5997	229	1.89	8.133	585.047	100.377	0	0.415	1
	Direction	*max*	*min*	*min*	*min*	*min*	*min*	*min*	*max*	*max*	*min*

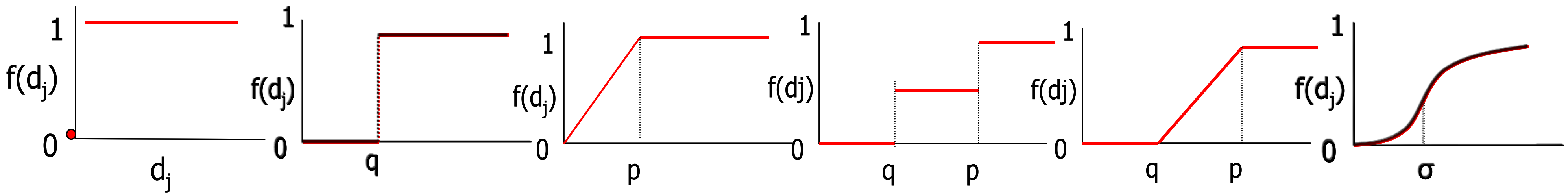
[1] For all economic criteria, the average daily wage in the Ethiopian context was assumed to be 13 $/day.
[2] A discount rate of 8% was assumed for the calculation.

Integration of problem in Multi-Criteria Decision Analysis
The PROMETHEE method

- Outranking method – Construction of an outranking relation
- Pairwise comparison of alternatives in each criterion → Calculation of **partial preference indexes**

$$P_j(a,b) = f\left(d_j\right) \rightarrow [0,1]$$

- The analyst can select among 6 different criteria specifications accepting indifference (q) and/or preference (p) thresholds as well as intermediate preference states.



1. **Usual criterion:** assumes abrupt transition from indifference to preference without thresholds
3. **V-type criterion with linear preference:** only preference threshold
4. **Level criterion:** there is only one value between indifference and strict preference
5. **Linear criterion:** includes indifference threshold and linear transition to the strict preference situation defined by the preference threshold

Integration of problem in Multi-Criteria Decision Analysis

The PROMETHEE method

- **Multicriteria preference index**

$$\mathit{\Pi}(a,b) = \frac{\sum_{j-1}^{m} w_j \times P_j(a,b)}{\sum_{j=1}^{m} w_j}$$

- Represents the intensity of preference of alternative a over alternative b

Leaving flow: $\varphi^+(\alpha) = \sum_{i=1}^{n} \Pi(a,i)$

Entering flow: $\varphi^-(\alpha) = \sum_{i=1}^{n} \Pi(i,a)$

PROMETHEE I

- Leaving flow gives the outranking character of the corresponding alternative while entering flow gives the outranked character of the corresponding alternative.

Net flow: $\varphi(\alpha) = \varphi^+(\alpha) - \varphi^-(\alpha)$

PROMETHEE II

If $\varphi(a) > \varphi(b)$, alternative a outranks alternative b

Integration of different stakeholder viewpoints

Two sets of criteria

Local investor's viewpoint

INDICATOR	UNIT	DIRECTION	RANGE OF VALUES	TYPE	THRESHOLDS	CATEGORY
Initial investment	€	Min	≥ 0	4	q=50, p=200	Economic
Annual O&M costs	€/year	Min	≥ 0	4	q=5, p=20	Economic
Levelized Generating Cost	€/kWh	Min	≥ 0	3	p=0.05	Economic
Availability	-	Max	0 – 1	3	p=0.05	Technical
Local to national labour	-	Max	0 - 1	5	q=0.01, p=0.05	Social

National policymaker's viewpoint

INDICATOR	UNIT	DIRECTION	RANGE OF VALUES	TYPE	THRESHOLDS	CATEGORY
Non-renewable primary energy	MJ/kWh	Min	≥ 0	4	q=0.1, p=1	Environmental
Global warming	g $CO2_{eq}$/kWh	Min	≥ 0	4	q=5, p=50	Environmental
Metal depletion	g Fe_{eq}/kWh	Min	≥ 0	4	q=0.5, p=5	Environmental
Levelized Generating Cost	€/kWh	Min	≥ 0	3	p=0.05	Economic
National to total expenses	-	Max	0 – 1	5	q=0.01, p=0.05	Social
Local to national labour	-	Max	0 – 1	5	q=0.01, p=0.05	Social
Institutional burden	Qualitative	Min	Very low - Very high	1	-	Institutional

PROMETHEE II: Ranking for different weighting schemes

Investor's viewpoint

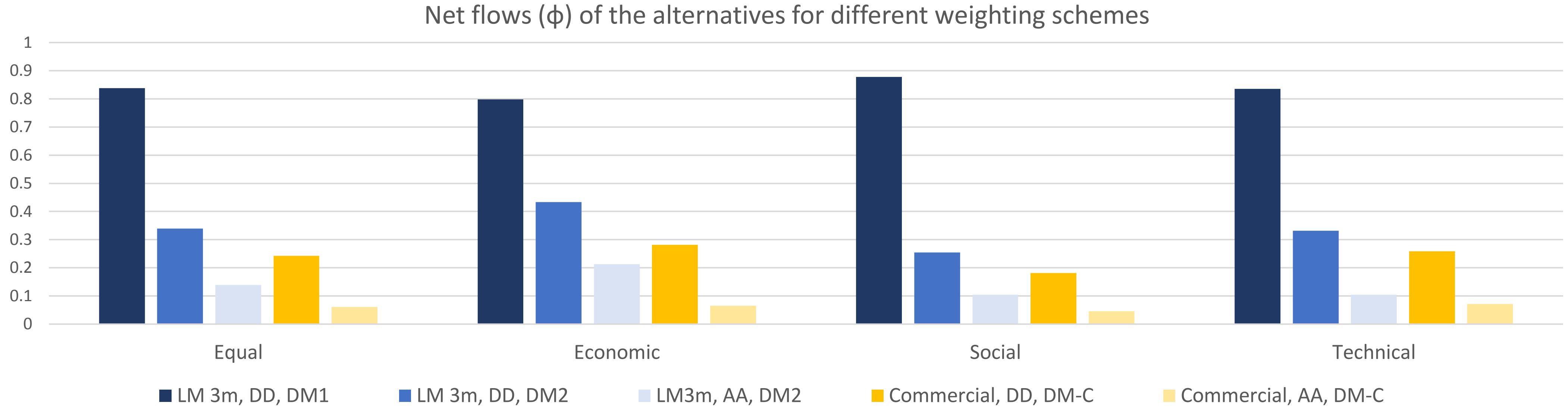
Equal focus in categories
- Social: 33,3%
- Economic: 33,3%
- Technical: 33,3%

Economic focus
- Social: 25%
- **Economic: 50%**
- Technical: 25%

Technical focus
- Social: 25%
- Economic: 25%
- **Technical: 50%**

Social focus
- **Social: 50%**
- Economic: 25%
- Technical: 25%

Investor's viewpoint



Ranking	Equal	Economic	Social	Technical
LM 3m, DM1	1	1	1	1
LM 3m, DM2, DD	2	2	2	2
LM3m, DM2, AA	4	4	4	4
Commercial, DM-C, DD	3	3	3	3
Commercial, DM-C, AA	5	5	5	5

PROMETHEE II: Ranking for different weighting schemes

Policymaker's viewpoint

Equal focus in categories
- Social: 25%
- Environmental: 25%
- Economic: 25%
- Institutional: 25%

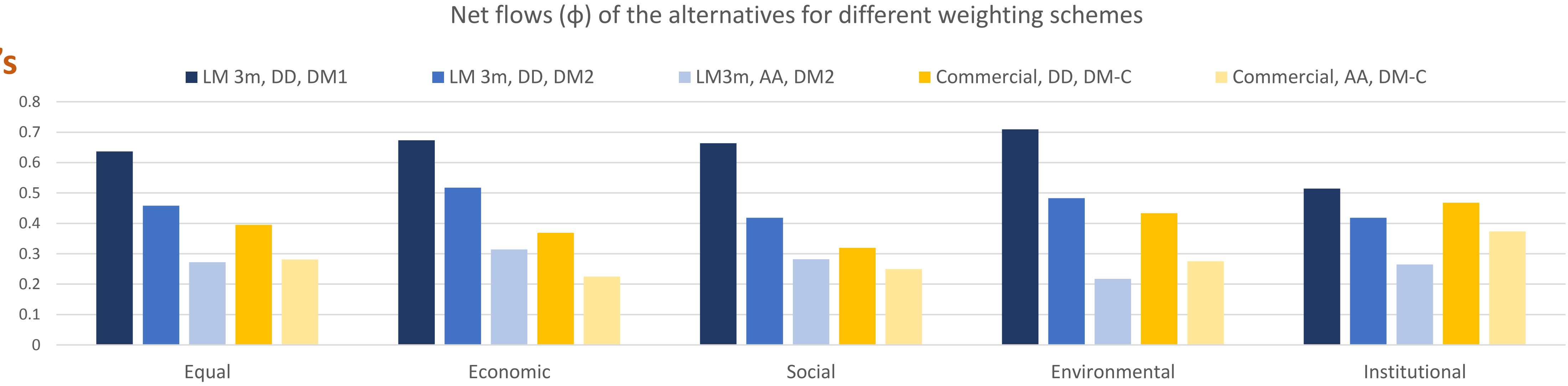
Economic focus
- Social: 20%
- Environmental: 20%
- **Economic: 40%**
- Institutional: 20%

Social focus
- **Social: 40%**
- Environmental: 20%
- Economic: 20%
- Institutional: 20%

Environmental focus
- Social: 20%
- **Environmental: 40%**
- Economic: 20%
- Institutional: 20%

Institutional focus
- Social: 20%
- Environmental: 20%
- Economic: 20%
- **Institutional: 40%**

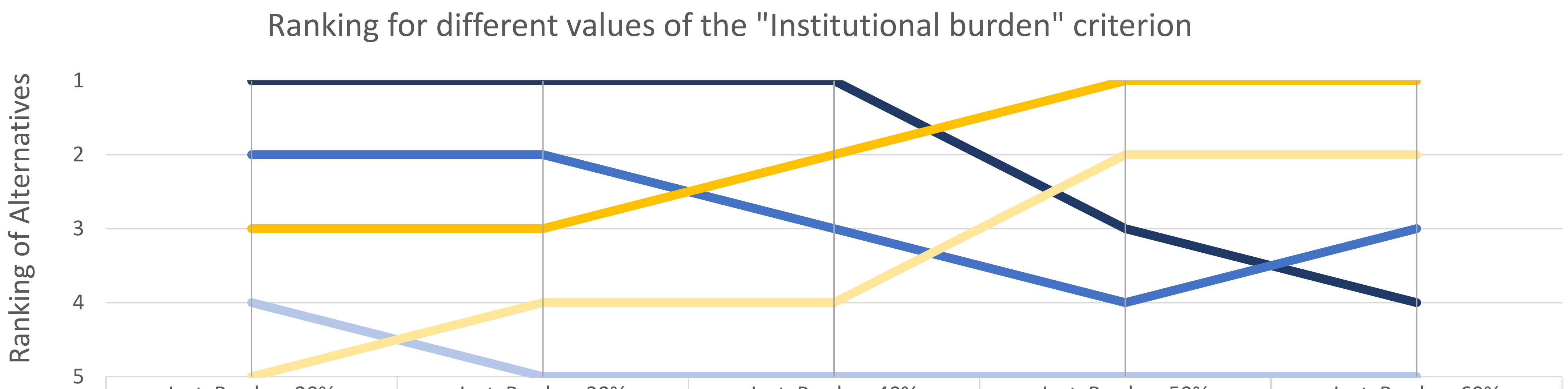
Policymaker's viewpoint



Multicriteria flows	Equal	Economic	Social	Environmental	Institutional
LM 3m, DM1	1	1	1	1	1
LM 3m, DM2, DD	2	2	2	2	3
LM3m, DM2, AA	5	4	4	5	5
Commercial, DM-C, DD	3	3	3	3	2
Commercial, DM-C, AA	4	5	5	4	4

Sensitivity analysis

Institutional criterion



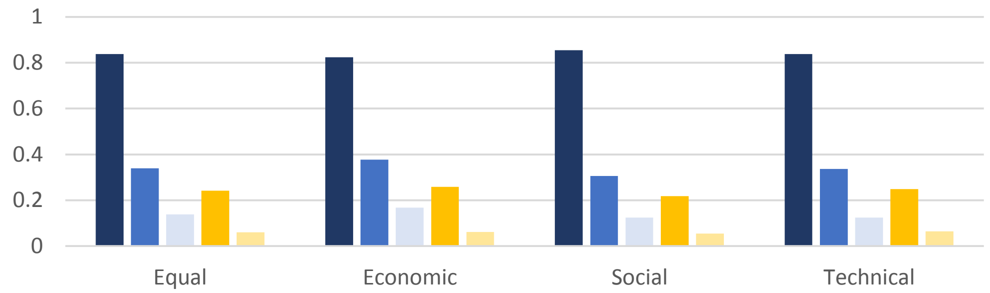
	Inst. Burden: 20%	Inst. Burden: 30%	Inst. Burden: 40%	Inst. Burden: 50%	Inst. Burden: 60%
LM 3m, DD, DM1	1	1	1	3	4
LM 3m, DD, DM2	2	2	3	4	3
LM3m, AA, DM2	4	5	5	5	5
Commercial, DD, DM-C	3	3	2	1	1
Commercial, AA, DM-C	5	4	4	2	2

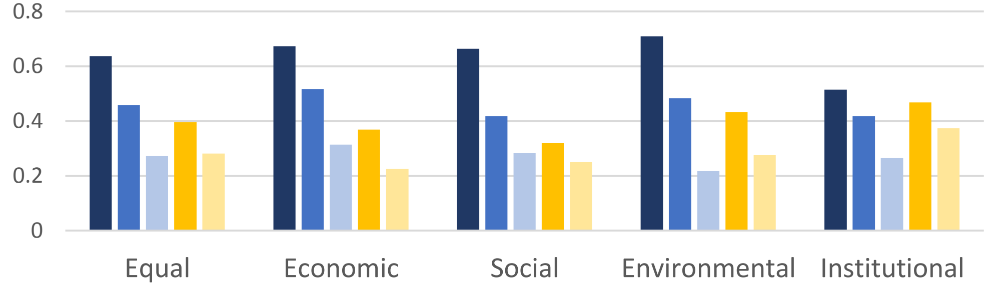
- Preference of commercial alternative increases
- Preference of LMSWTs decreases
- For weights ≥ 0.5 commercial alternative A4 ranked first - A1 third

- Institutional burden for supporting LMSWTs outweighs all economic, social and environmental benefits they bring
- Expert elicitation required to define weight and performance in this criterion

Conclusions

- Investors
  - Local manufacture and local maintenance clearly preferred
  - Local manufacture is preferred even without local maintenance
  - Low ranking for commercial SWT
- Policymakers
  - Local manufacture and local maintenance preferred in all cases
  - Local manufacture not always preferred to the commercial alternative
  - For Inst. criterion weight ≥ 0.5, commercial wind turbine ranked first
  - Expert elicitation to define weight and performance in this criterion





- General
  - ❑ Local manufacture combined with Local maintenance more sustainable than all other alternatives
  - ❑ Without local maintenance can be less sustainable than commercial
  - ❑ Main weakness of the LM-LM solution is the institutional burden it may require – Needs to be further examined

  - ❑ Solution should be considered in rural electrification projects
  - ❑ Significant advantages in social, economic and environmental categories
  - ❑ **Its advantages are not due to technological progress - Rather on the way the technology is employed**
  - ❑ Can provide a solution for rural electrification that aligns with the agroecological vision of Bioeconomy


Thank you!