Multi-criteria evaluation of transition pathways towards a sustainable energy system

1. Problem Motivation: Research project on sustainable electricity supply
2. Research question and research gap
3. Application of MCDA to evaluate transition pathways with time-varying criteria (Status quo)
4. Questions and challenges for further research

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University of Göttingen (Germany)

- Founded in 1734
- 13 Faculties with 27,500 students and 12,000 staff members (495 professors)
- 45 Nobel price laureates are linked to Göttingen via their CV (2014: Stefan Hell (Chemistry) for "for the development of super-resolved fluorescence microscopy")

Chair of Production and Logistics
(Faculty of Economic Sciences)
12 Research Associates / Ph.D. students working on current topics of sustainability and energy efficiency, using methods of Operations Research
Transformation of the Energy Supply System

Energy supply in former days:

- Large-scale power plants
  - 380/220 kV
  - 110 kV
  - 20 kV
  - 0,4 kV
- Industry/business units
- Households

Energy supply in future:

- Flexible power plants
  - Offshore-Windpower
  - Onshore-Windfarm
  - Biogas plant
  - Wind power plant
- Large-scale storage
- Industry
- Industry/business unit
- Storage
- PV-parks
- Co-generation
- E-mobility

Households
Energy mix pathway

Pathway 1

Pathway 2

Structure of the Primary Energy consumption in Germany for two different scenarios (BMU, 2012)
Transition pathways towards a sustainable electricity supply for Lower-Saxony
Transition pathways towards a sustainable electricity supply for Lower-Saxony

**Issue**

- **Targets:**
  - Reduction of GHG emissions by 80%-95% in 2050 compared to 1990
  - Nuclear phase-out
- **Transformation of the energy system with increased use of renewable energy**
- **Multiple conflicting objectives**

**Energy mix?**

- **Environmental sustainability**
- **Economic competitiveness**
- **Social acceptance and wellbeing**
- **Security of supply**
- **Grid expansion with more fluctuating energy production?**
- **Information technology to flexibilize energy demand?**

- **Electricity storage?**

Funded by Ministry of Science and Culture
Status quo

Electricity Mix 2014

Abbildung 8: Energieflussbild Niedersachsen 2012 (Angaben in Petajoule)

Erneuerbare Energien 26%
Braunkohle 25%
Kernenergie 16%
Steinkohle 18%
Mineralöl 2%
Erdgas 10%
Sonstige 4%
Research questions within NEDS

What are possible transition pathways towards a sustainable electricity supply for Lower Saxony in 2050?

How can we evaluate the sustainability of the different transition pathways?

- Transition takes a long time
- Various stakeholder groups
- Conflicting criteria from economic, ecological, technological and social perspective

Use of Multi-criteria decision analysis

Bandwidth of the total electricity generation from renewable energies for different scenarios with goal of 80% GHG emissions reduction in 2050 (BMU, 2012)
## Sustainability of energy systems: Related Research

<table>
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<th>Energy scenarios (Germany)</th>
<th>MCDA &amp; Energy scenarios</th>
<th>Time-dependent MCDA</th>
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<td><strong>Objective</strong></td>
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<tr>
<td>• Forecasting/Backcasting of scenarios for 2050</td>
<td>• MCDA for decision between different energy scenarios</td>
<td>• MCDA for long-term, multi-period decisions</td>
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<tr>
<td>• Explorative and normative scenarios</td>
<td>• Different MCDA methods applied</td>
<td>• Uncertainty in evaluation is tackled e.g. through scenario analysis, probabilities, fuzzy numbers</td>
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<tr>
<td>• Energy system modelling</td>
<td>• Consideration of technical, social, ecological and economic criteria</td>
<td>• Alternatives are static</td>
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<td>• Consideration of sustainability through cost and CO₂</td>
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<td>• One multi-period approach</td>
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<th><strong>Selected papers</strong></th>
<th><strong>Diakoulaki &amp; Karangelis (2007)</strong></th>
<th><strong>Frini &amp; BenAmor (2014)</strong></th>
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<td>Kronenberg et al. (2011)</td>
<td>Wang et al. (2009)</td>
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<td>Oberschmidt (2010)</td>
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<th><strong>Research Gap</strong></th>
<th><strong>Study for a federal state (Lower-Saxony)</strong></th>
<th><strong>Consideration of pathways with time- varying criteria values (“multi-period MCDA”)</strong></th>
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<td>Modeling different sustainability criteria besides CO₂ emissions and cost</td>
<td>Connection of different modeling tools</td>
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Grid simulation of alternatives (Hoffmann & Blaufuß)
Methodological framework

Future scenarios (framework conditions)

Identification of relevant parameters for alternative energy supply

Determination of sustainability criteria

Economic model

Technical model

Social model

Ecological model

Multi-criteria decision analysis

Stakeholder participation

Illustration based on Hoffmann (2015)
Multi-criteria decision analysis – General process

1. Identification of the problem / issue
2. Problem structuring
   - Values
   - Goals
   - Stakeholders
   - Constraints
   - External Environment
   - Key issues
   - Alternatives
   - Uncertainties
3. Model Building
   - Defining criteria
   - Specifying alternatives
   - Eliciting values
   - Synthesis of information
4. Using the model to inform and challenge thinking
   - Challenging intuition
   - Creating new alternatives
   - Sensitivity analysis
   - Robustness analysis
5. Developing an action plan

Belton and Stewart (2002)
• Criteria have been developed by research team based on the results from public symposium and literature
• In total 33 criteria
• Challenge: Redundancy and independence of criteria with participation
Formal decision problem for MCDA

Set of discrete alternatives
(here: *transition pathways*)

\[ A := \{a_1, ..., a_i, ..., a_m\} \]

Set of decision criteria
(here: *sustainability criteria*)

\[ C := \{c_1, ..., c_j, ..., c_n\} \]

Criteria values:

\[ x_{ij} = f_j(a_i), j = 1, ..., n, i = 1, ..., m \]

\[ x_{ijt} = f_{jt}(a_i) \text{ or } x_{ijt} = f_j(a_i, t) \]

\[ j = 1, ..., n; i = 1, ..., m, t = 1, ..., T \]
Evaluation of transition pathways: Time-varying alternatives

MCDA per time step:
One ranking per time step

MCDA with time-dependent criteria values

System state 2015
Technical criteria
Economic criteria
Social criteria
Ecological criteria

Target state 2050
Technical criteria
Economic criteria
Social criteria
Ecological criteria

MCDA Evaluation at discrete time steps

Criteria values for one criterion over time

$\Phi_{\text{net}}(a_t, t)$

$f_{jt}(a_t)$

Alternative 1
Alternative 2
Alternative 3

$\text{t=1, t=2, t=3, t=4}$

$\text{t=1, t=2, t=3, t=4}$
Why is it important to account for the time component in MCDA?

**Distributional aspects**
- Distribution of costs and benefits over time
- Intergenerational justice

**Uncertainties in long-term decision making**
- Technological change
- Values and behaviour changes over time
- Political and and economic framework conditions
- Interdependencies

**Behavioural research (Psychology/ Economics)**
- Intertemporal Preferences*
- Behavioural bias

*Berns et al. (2007), Loewenstein et. al (2002)
PROMETHEE
Preference Ranking Organisation Method for Enrichment Evaluations*

(1) Definition of preference function $P_j(d)$ for each criterion $j$ with
\[ d = f_j(a_i) - f_j(a_i^*) \]

(2) Definition of the **weighting vector** $w^T := \{w_1, ..., w_j, ..., w_n\}$

(3) Calculation of **preference index**, which is a measure for the preference of an alternative $a_i$ over alternative $a_i^*$ considering all criteria
\[ \pi(a_i, a_i^*) = \sum_{j=1}^{m} w_j P_j(x_{ik} - x_{i^*k}) \]

(4) Calculation of **outflow** as a measure
for the strength of an alternative $a_i$:
\[ \Phi^+(a_i^*) = \frac{1}{n-1} \cdot \sum_{i=1}^{n} \pi(a_i^*, a_i) \]

(5) Calculation of **inflow** as a measure
for the weakness of alternative $a_i$:
\[ \Phi^-(a_i^*) = \frac{1}{n-1} \cdot \sum_{i=1}^{n} \pi(a_i, a_i^*) \]

(6) Determination of **ranking**:

**Partial ranking**

- **Complete ranking**

Based on Netflow:
\[ \Phi^{net}(a_i) = \Phi^+(a_i) - \Phi^-(a_i) \]

*Brans et al. (1986)*
Possible ways to handle time-varying data for PROMETHEE

Determination of criteria values:
Aggregation of criteria values over time, e.g. \( x_{ij} = \frac{1}{T} \sum_{t=1}^{T} f_{jt}(a_i), j = 1, \ldots, n, i = 1, \ldots, m \)

Determination of criteria weights \( w_j \):
Time-dependent weights

Determination of preference functions \( P_j \):
• Weighting of preferences over time* ("discounting of preferences") \( \bar{P}_j(a_i^*, a_i) = \sum_{t=1}^{T} \alpha \cdot p_j(f_{jt}(a_i^*) - f_{jt}(a_i)) \) mit \( \alpha = \frac{1}{1 + \beta_t} \)
• Time-dependent preference functions, e.g. varying threshold values**

Calculation of preference index or flows:
Calculation of outranking per time step and aggregate using weights for time steps

Questions and challenges for further research

Implementation of research methodology:

How to link MCDA to the results of other modeling tools? Is this possible/reasonable?

Participation in complex decision problems:

How to deal with different stakeholder groups where nobody is the actual decision maker?
How much participation is constructive?

Long-term decision making and time-component in MCDA:

How to deal with decisions affecting a long time horizon?
Which modification of the method is appropriate and well-founded to account for the time-varying criteria values?
Literature (1/3)


Literature (3/3)


