Insights from the Center for Industrial Ecology - University of Coimbra

Fausto Freire
Outline

- University of Coimbra, Portugal

- CIE: history, team, Research Agenda, projects ....

- Selected Research examples:
  - Agri-food and Forestry
  - Biofuels
  - Electricity in Portugal
University of Coimbra

UNESCO World Heritage List

Founded in 1290, more than 20,000 students, 1500 Professors
Research group in the multi-disciplinary field of Industrial Ecology, part of ADAI-Associated Lab for Energy, Transports & Aeronautics.

Team of faculty, researchers, Doctoral candidates, and visiting scholars. Research is carried out in collaboration with other institutions and with international partners.

The CIE is actively involved in the Energy for Sustainability Initiative at the Univ. of Coimbra and in the MIT-Portugal program (PhD in Sustainable Energy Systems).

Develops and applies tools to enhance the sustainability of products and systems supported by life-cycle thinking.

Takes a holistic and systematic approach to promote sustainable systems and R&D&I with industry, public authorities, organizations...
Team
CIE team

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DOI: 10.1007/s11097-014-0574-3

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Research Agenda

- Environmental life-cycle assessment (Carbon, water, environmental footprints)
- Social LCA, Life-cycle management, LC Costing
- Life-cycle sustainability assessment
- LCA & multi-objective optimization, LCA & Partial Equilibrium Analysis (LCAA)
- LCA & MultiCriteria Decision Analysis
- Extended LC approaches: uncertainty, variability, local aspects & spatial different
- Eco-design, fleet-based LCA, Dynamics
- Urban metabolism & Material Flow Analysis, MFA & LCA
Main Application areas

- **Energy** | Bioenergy, biofuels, & other renewables, electricity, natural gas,

- **Agrifood and Forestry** | fruits, vegetables, vegetable oils, animal-derived products, sustainable diets, wood-based materials, LUC

- **Transportation** | sustainable mobility, vehicle components and systems (electric vehicles, trains, fleet analysis, batteries), powertrains

- **Buildings and Sustainable Architecture** | building components, prefabrication, sustainable construction and retrofit, thermal insulation, sustainable urban development

- **Waste management** | waste cooking oil, demilitarization, wastewater management, anaerobic digestion, building waste management, beef tallow

- **Industrial Systems, Packaging**
## Ongoing projects

<table>
<thead>
<tr>
<th>Year</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016-2019</td>
<td>SABIOS: Sustainability assessment of bioenergy systems: a life cycle multi-criteria decision-support approach, including land use change</td>
</tr>
<tr>
<td>2016-2019</td>
<td>SUSTAINFOR: Sustainability assessment of forest sector management strategies in the context of a bioeconomy</td>
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<tr>
<td>2016-2019</td>
<td>UrbanWins: Urban metabolism accounts for building waste management innovative network strategies</td>
</tr>
<tr>
<td>2016-2017</td>
<td>BIO2URBAN: Biodiesel blends for road vehicles in urban areas</td>
</tr>
<tr>
<td>2018</td>
<td>LCA and Ecodesign of packaging for pharmaceutical products</td>
</tr>
</tbody>
</table>
Concluded projects

Funded by Companies

• ROLLS-ROYCE Environment Advisory Board
  2015-16: Lifecycle GHG Analysis of Train Power Systems: Diesel, Hybrid and LNG

• Portuguese Association of Biofuel Producers – APPB
  2014-16: LCA of GHG emissions for rapeseed-based biodiesel in Portugal
  2010-11: LCA of GHG emissions for soybean-based biodiesel in Portugal

• CIE Plasfil – Automotive Plastic components producer
  2013-15: EDIL - EcoDesign and Impact Labelling

with international partners

• 2010-14: Capturing Uncertainty in Biofuels for Transportation, MIT, USA,
• 2010-14: Economic and Env. Sustainability of Electric Vehicle Syst. USA, MIT
• 2013-15: LC Environmental Sustainability Assessment of Bioenergy USP, Brazil
• 2011-13: BIOACV – Comparative LCA of Biodiesel from Soybean Oil and Animal Fat, Methylc and Ethylic Routes USP, Brazil
• 2011-15 Environmentally Responsible Munitions, several EU
Concluded projects

National projects

• 2012-2015: **BioHeavy** - Extended “well-to-wheels” assessment of biodiesel for heavy transport vehicles

• 2013-2015: **BioSustain** - Sustainable mobility: Perspectives for the future of biofuel production - Sustainable mobility: Perspectives for the future of biofuel production

• 2007-2011: Biofuel systems for transportation in Portugal: A "well-to-wheels" integrated multi-objective assessment

• 2012-2015: **EMSURE** - Energy and Mobility for Sustainable Regions

• 2011-2013: **EcoDeep** - Eco-efficiency and Eco-management in Agro-industry
Selected Research from

- Agri-food and Forestry
- Biofuels
- Electricity in Portugal
Agrifood and Forestry

- Sunflower
- Chestnut
- Olive oil
- Dairy products
- Wood-based materials
LCA of sunflower cultivation in PT

- Irrigated vs rainfed
- LUC scenarios
- Different functional units (kg and ha)
- Uncertainty analysis

LCA of fresh and frozen chestnut

- Portugal is the 3rd largest producer of chestnut in Europe (EU 28)
- Annual production of 27 thousand tons
- Orchard area of 35 thousand hectares
- 70-80% of Portuguese chestnut is exported

Objective: Environmental impacts of fresh and frozen chestnut produced in Portugal (for exports and national consumption).

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LC impacts of fresh and frozen chestnut

LCA of olive oil addressing alternative production systems

- Large variety of cultivation systems (familiar, traditional, intensive and organic)
- Two main technologies for olive oil extraction
- To assess the influence of the multifunctionality approach (allocation vs substitution)

- Three-phase
  - Olive oil, pomace & wastewater

- Two-phase
  - Olive oil & wet pomace

**Olive pomace is recovered** to produce **olive pomace oil** & **extracted pomace** (chemical extraction with hexane)
LC model addressing valorization of pomace

Olive cultivation
- Familiar: 0.4 t ha⁻¹
- Traditional: 1.8 t ha⁻¹
- Intensive: 10 t ha⁻¹
- Organic: 0.5 t ha⁻¹

1. Olive oil extraction & packaging
   - Olive oil (1.0 L)
   - Olives: 5.3 kg (4.8-5.9)

2. 2-phase extraction
   - Olive oil extraction & packaging

3. 3-phase extraction
   - Olive oil extraction & packaging
   - Pomace: 3.0 kg
   - Olive stones & leaves: 0.8 kg
   - Treated wastewater: 4.8 L

- Olive pomace oil (0.2 kg)
- Extracted pomace (1.6 kg)
- Olive oil (1.0 L)
- Wastewater (0.5 L)
- Olive stones & leaves (0.7 kg)

- Drying & extraction of olive pomace oil
  - Extracted pomace (0.1 kg)
  - Extracted pomace (0.2 kg)
  - Wet pomace: 4.6 kg
  - Olive pomace oil: 0.1 kg

- Drying & extraction of olive pomace oil
  - Extracted pomace: 0.8 kg
LCA of olive oil

- Cultivation is the LC phase which contributed the most to the overall impacts.
- The high olive productivity of the intensive production system leads to comparatively low impacts.

Impacts of different olive cultivation systems

But: How comparable are the different systems and types of olive oils? (organic, familiar, intensive)
Biofuels

- LCA of biodiesel:
  - Virgin oils – rapeseed, palm, soybean, sunflower
  - Microalgae
  - Waste cooking oils
  - Beef tallow

- LCA of bioethanol:
  - Wheat
  - Sugar beet
  - Sugarcane

- Well-to-Tank & Tank-to-Wheels analysis
- Land Use Change (LUC)
- Agriculture practices and pathways
- Uncertainty analysis
- Multicriteria decision analysis
- Multi-objective optimization
- Social impacts
- Water footprint
- Multifunctionality
LCA of biofuels: sources of uncertainty

- Soil emissions (LU / LUC)
- Assessment of co-products
- LCA approach (attributional/consequential)
- Prior land use
- Temporal/geographical scale
- System boundaries
- Capital goods
- Functional unit
- Reference system
- Parameter uncertainty

**Methodological Challenges affecting the Results of Biofuel LC Studies**

LCA of EU Rape methyl ester ester
A Review

- Biofuel LC studies have varying and sometimes contradictory conclusions, even for the same biofuel type and pathway.
- Significant disagreement and controversy exist regarding the actual benefits of biofuels displacing fossil fuels.

LCA of rapeseed biodiesel

Main contributions to the environmental impacts of rapeseed cultivation in various countries

- Contribution of substances to GW
  - **LUC scenarios**: LUC#1 (low inputs) and LUC#2 (high inputs)
  - **Climates**: WTM - warm temperate moist; CTD - cool temperate dry; CTM - cool temperate moist
  - **Fertilization scenarios**: FS#1 (N as NPK+CAN) and FS#2 (N as NPK+U)


LCA of biodiesel produced with palm oil from Colombia

- Alternative fertilization schemes:
  - Ammonium sulphate - #AS
  - Ammonium nitrate - #AN
  - Calcium ammonium nitrate - #CAN
  - Urea - #U
  - Poultry manure - #Poultry

- Comparison of LCIA methods

- Biogas captured and flared vs released
LCA of biodiesel produced with palm oil from Colombia

LUC @ Colombia (1990-2010)


LC GHG intensity of soybean biodiesel

- Three pathways and four Brazilian soybean origins

Contribution of each LC phase for GHG intensity

Pathways
C1: Biodiesel produced in Brazil | C2: Biodiesel produced in Portugal based on imported Brazilian soybean oil | C3: Biodiesel produced in Portugal based on imported Brazilian soybean

Soybean origins (Brazilian states)
MT: Mato Grosso | GO: Goiás | PR: Paraná | RS: Rio Grande do Sul


LCA of soybean cultivation in Brazil

LCIA of soybean cultivation in four Brazilian states:

- Mato Grosso
- Goiás
- Paraná
- Rio Grande do Sul

GHG intensity (g CO$_2$eq MJ$^{-1}$)
Terrestrial acidification (g SO$_2$eq MJ$^{-1}$)
Marine eutrophication (g Neq MJ$^{-1}$)
Freshwater eutrophication (mg Peq MJ$^{-1}$)
Ozone depletion ($10^{-6}$g CFC-11eq MJ$^{-1}$)
Human toxicity (g 1,4-DBeq MJ$^{-1}$)
Terrestrial ecotoxicity (g 1,4-DBeq MJ$^{-1}$)
Freshwater ecotoxicity (g 1,4-DBeq MJ$^{-1}$)
Marine ecotoxicity (g 1,4-DBeq MJ$^{-1}$)

- Fertilizer and pesticides application emissions
- Transport of inputs
- Fertilizers production
- Pesticides production
- Diesel production and use

MT: Mato Grosso
GO: Goiás
PR: Paraná
RS: Rio Grande do Sul
LCA of Waste Cooking Oil biodiesel addressing uncertainty


Microalgae biodiesel

Comprehensive review of published LCAs for biodiesel produced from microalgae

- Identify the main causes for the high variability of GHG intensity
Multi-Criteria Decision Analysis (MCDA) and LCA: RME

- MCDA can be integrated in LCIA to support robust decisions in the interpretation phase of LCA
- A new LCIA-MCDA approach was applied to a comparative LCA of RME biodiesel to provide insights on the relative ranking of four rapeseed cultivation systems

Variable Interdependent Parameters Analysis (VIP Analysis)

<table>
<thead>
<tr>
<th>Summary</th>
<th>Range</th>
<th>Confrontation</th>
<th>Max Regret</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>-0.129</td>
<td>0.343</td>
<td>0.257</td>
</tr>
<tr>
<td>Canada</td>
<td>-0.087</td>
<td>0.2</td>
<td>0.072</td>
</tr>
<tr>
<td>Spain</td>
<td>0.065</td>
<td>0.395</td>
<td>0.195</td>
</tr>
<tr>
<td>France</td>
<td>0.065</td>
<td>0.395</td>
<td>0.257</td>
</tr>
</tbody>
</table>

Stochastic Multicriteria Acceptability Analysis (SMAA)
LCA of electricity in Portugal

LC model of electricity in Portugal addressing temporal variation – yearly and hourly
LCA of electricity in Portugal: GHG emissions and acidification

Yearly variability (2003-2014)

- Renewable share increased
- Variability between years mainly due to yearly variability in hydro generation
- High decrease in acidification impacts mainly due to the installation of gas treatment systems in coal power plants:
  - Desulfurization systems (to remove SO₂)
  - Denitrification systems (to remove NOx)

GHG emissions (kg CO₂ eq MWh⁻¹)

Acidification (kg SO₂ eq/MWh)

LCA of electricity in Portugal: Environmental impacts

Electricity GHG emissions
Hourly variability by month in Portugal (2012-2014)

- **High variability** in GHG emissions between hours, months and years
- Higher in the **first semester** (due to variability in hydro generation)

GHG emissions (g CO₂ eq kWh⁻¹)

126 g CO₂ eq kWh⁻¹

533 g CO₂ eq kWh⁻¹

Evolution of Consumption: Annual, month and hour variability (2007-2014)
Evolution of Total GHG Emissions: Annual, month and hour variability (2007-2014)
Evolution of GHG Emissions per kWh: Annual, month and hour variability (2007-2014)

GHG Emissions
(gCO₂eq/kWh)
(total by month and hour of day-grid)
Thank You!

Fausto Freire