THE UNIVERSITY OF BRITISH COLUMBIA
Faculty of Forestry

POLYTECHNIQUE MONTRÉAL
WORLD-CLASS ENGINEERING

BEST 402 Industrial Ecology – Professor Qingshi Tu

Interpreting Life Cycle Assessment (LCA) Results
Case Study: Fast Pyrolysis of Forest Biomass

Invited Lecture:

Paul Stuart

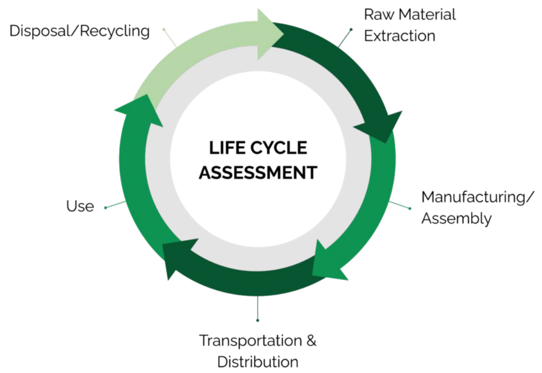
Department of Chemical Engineering – Polytechnique Montréal

*“**Aggregated Thoughts about LCA**”, based primarily on (1) the course GCH1220 on Life Cycle Design, (2) PhD thesis results of Dr Stéphanie Jean, and (3) consulting activities*

6 October 2022

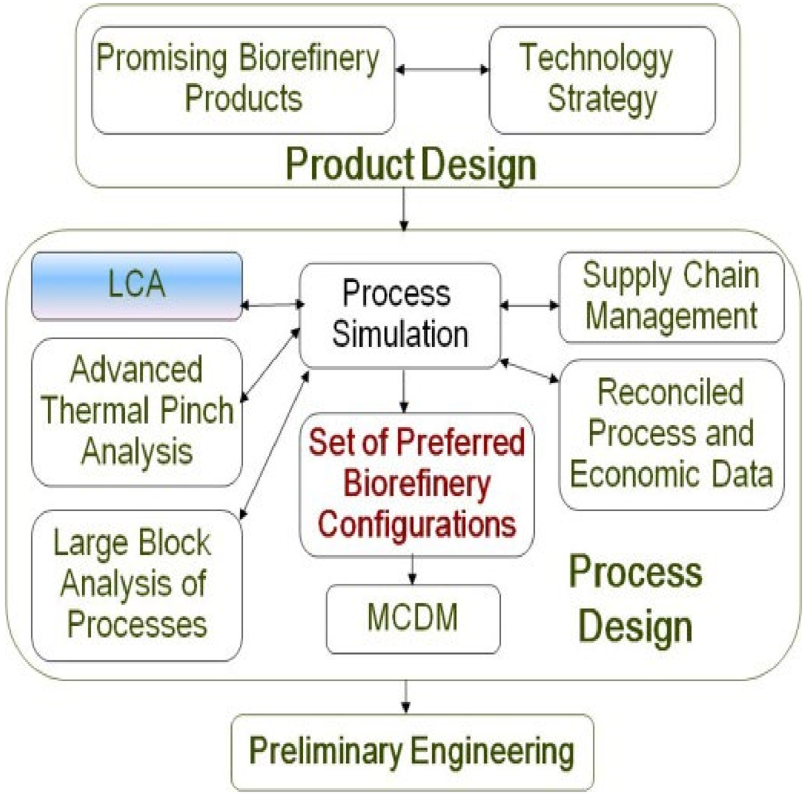
Objectives of this Lecture – Learning outcomes

- To present "**one perspective**" on the strengths and weaknesses of life cycle assessment (LCA)
- To give some insight into the **key methodological issues** that need to be addressed when using LCA for biorefinery design decision-making
- To introduce **MCDM panels** as an important design decision-making tool, and the context of environmental criteria
- To concretize the complexity of using LCA metrics for design decision-making: **interpreting LCA results** through presentation of a case study



Lecture Outline

- A **very very brief history** of LCA from the perspective of **design decision-making**
- Some **methodological questions** related to LCA and design decision-making that we have addressed in our research program over the years
- Design decision-making, **MCDM panels**, and LCA-based environmental criteria
- A **case study**, and **interpreting LCA results** for design decision-making
- **Ongoing research activities** and **take-home messages**



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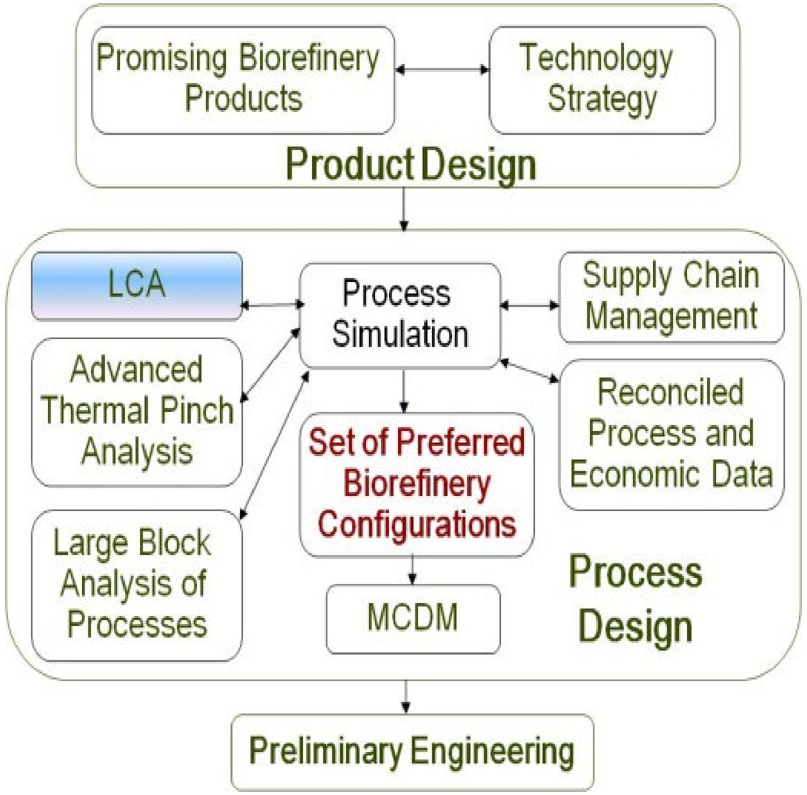
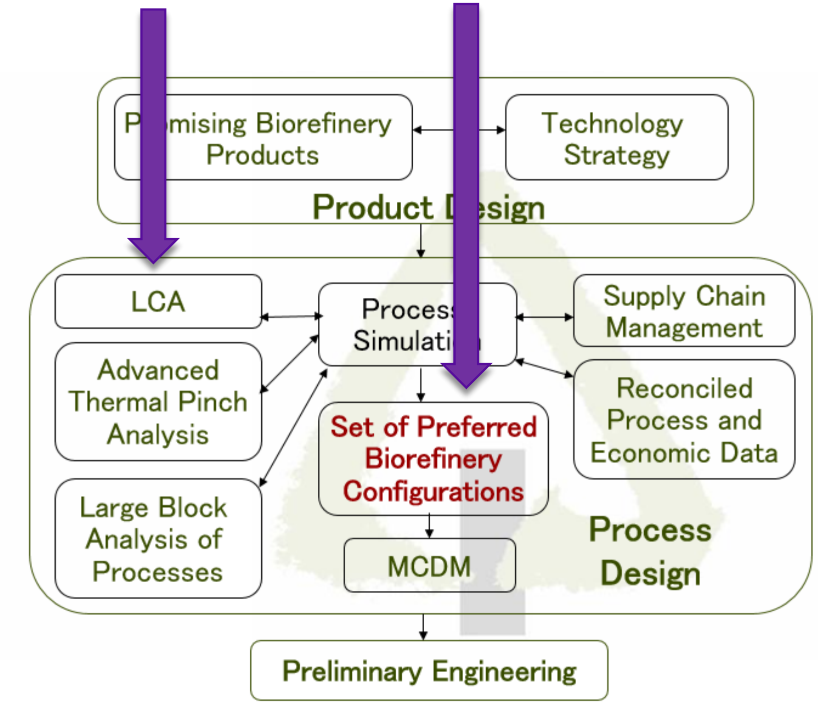


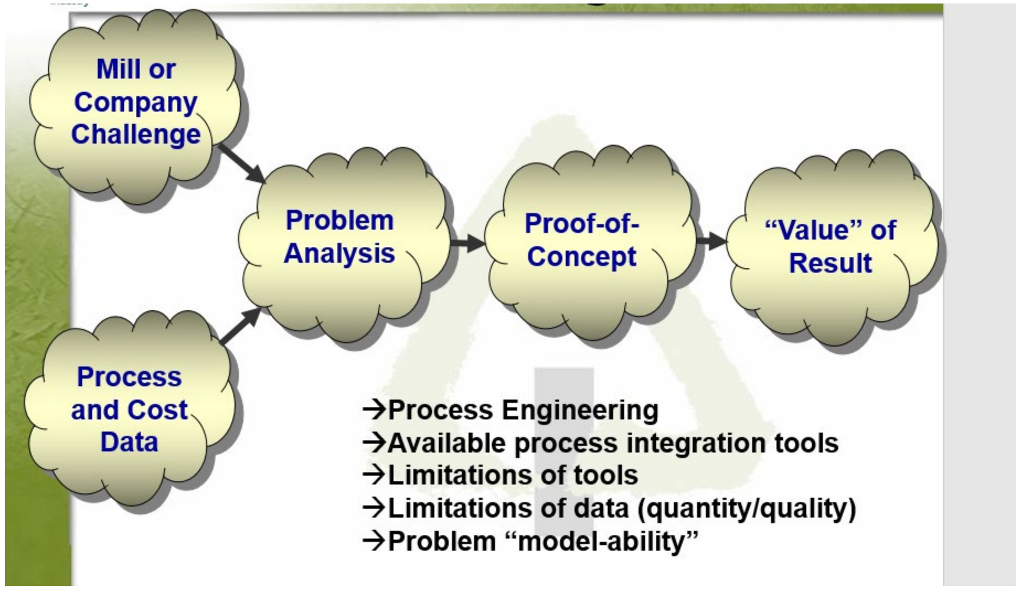
Product and Process Design Lab at Polytechnique

LCA is an important design tool…

Especially for design decision-making



Almost all our projects are done in close collaboration with industry partners



We use the design "toolbox" in our research, contributing (1) **methodologically** and through (2) **outcomes**

"Life Cycle Thinking" and "Life Cycle Design"

- The basis of "life cycle design", is "life cycle thinking"
- "Life Cycle **Thinking** (LCT) is about going beyond the traditional focus on production site and manufacturing processes, to include environmental, social and economic impacts of a product over its entire life cycle" (UNEP – Life Cycle Initiative - 2022)
- Life-Cycle **Design** (LCD) is the environmentally sound design of products based on the whole lifecycle starting from exploitation and processing of raw materials, …., to use and returning of materials over its entire life cycle

A Very Very Brief History of LCA…

PEER-REVIEWED **LIFE-CYCLE ASSESSMENT**

Life-cycle thinking in the pulp and paper industry, Part I: Current practices and most promising avenues

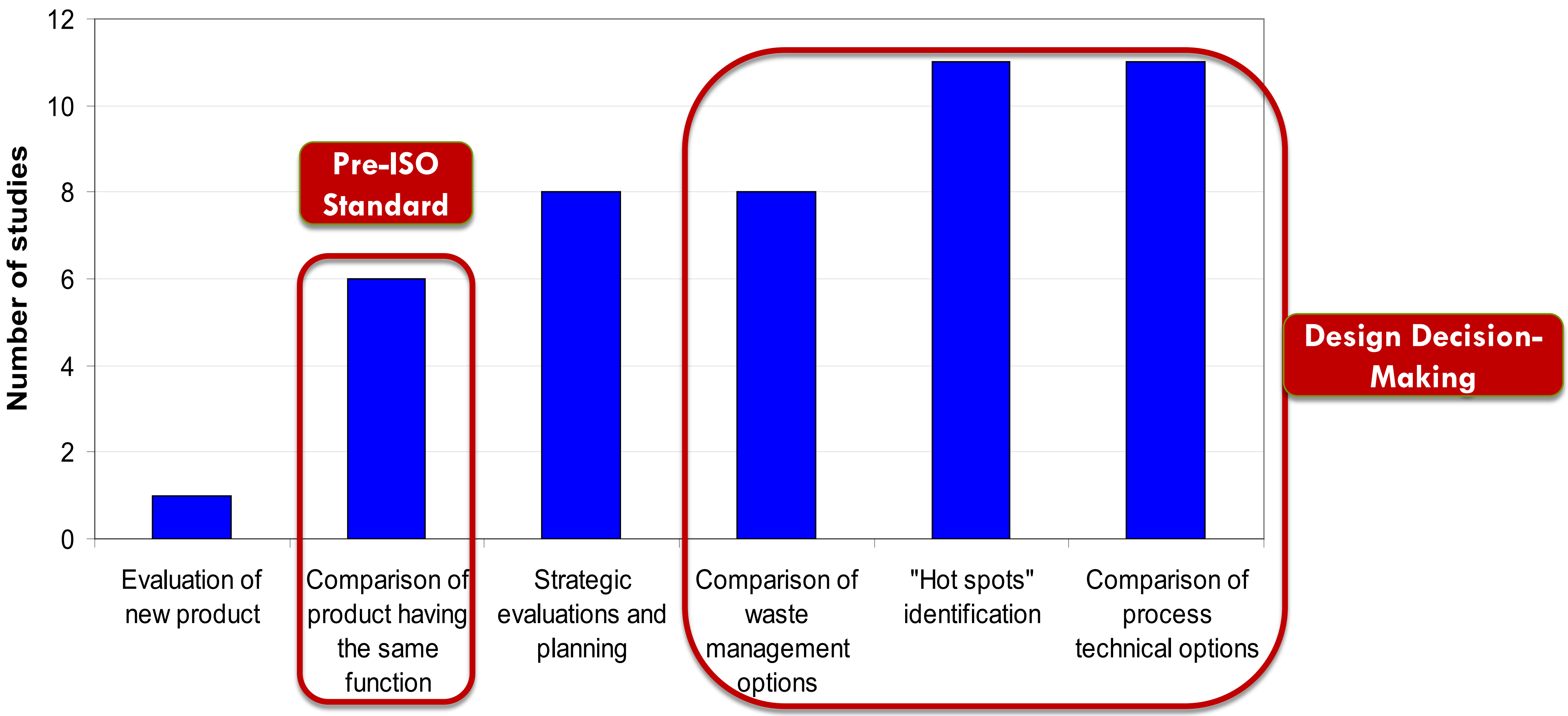
CAROLINE GAUDREAULT, RÉJEAN SAMSON, AND PAUL R. STUART

PEER-REVIEWED **LIFE-CYCLE ASSESSMENT**

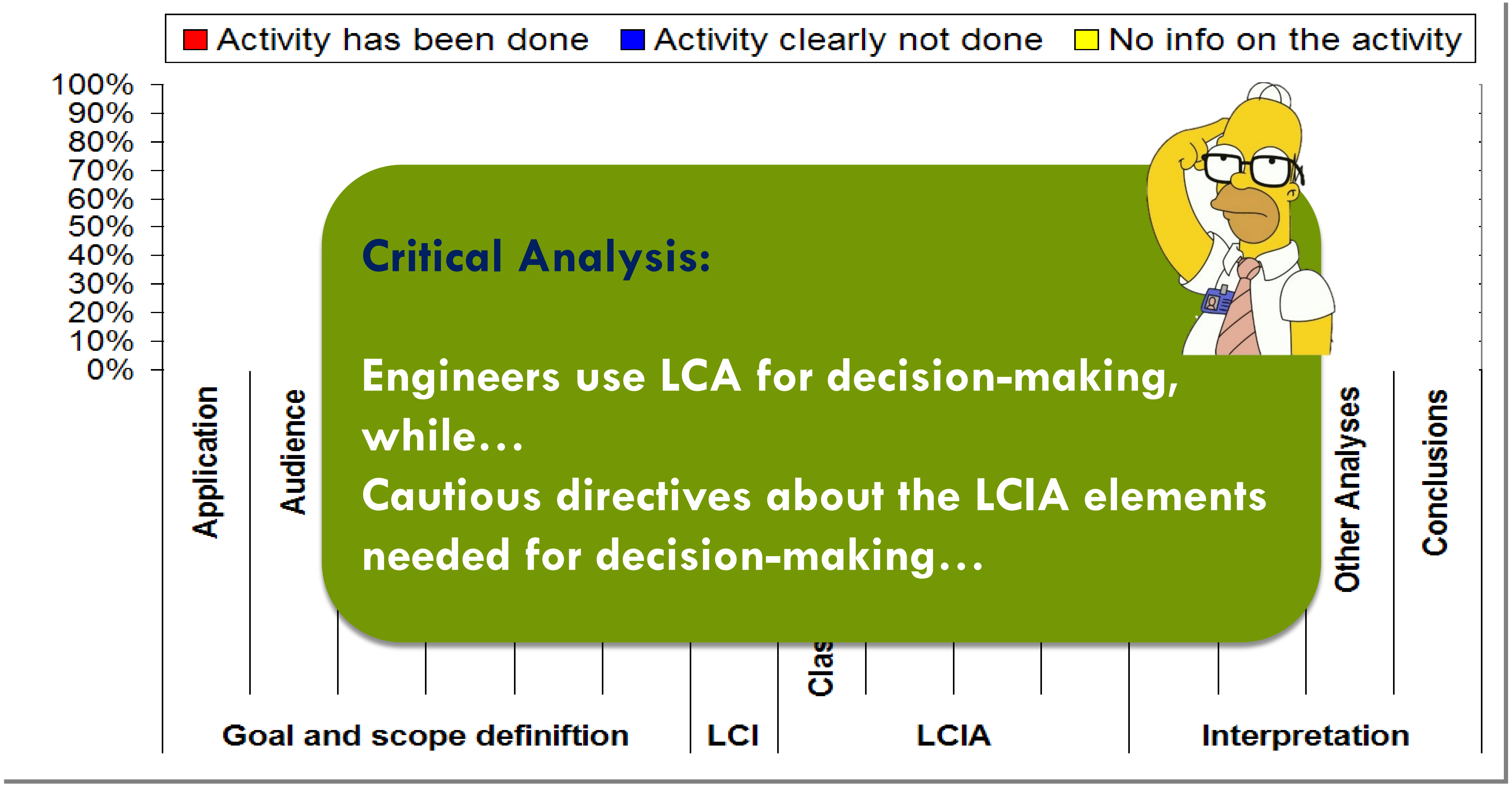
Life-cycle thinking in the pulp and paper industry, part 2: LCA studies and opportunities for development

CAROLINE GAUDREAULT, RÉJEAN SAMSON, AND PAUL R. STUART

A Very Very Brief History of LCA…



A Very Very Brief History of LCA…



Critical Analysis:

Engineers use LCA for decision-making, while…
Cautious directives about the LCIA elements needed for decision-making…

LCA “Completeness Analysis”

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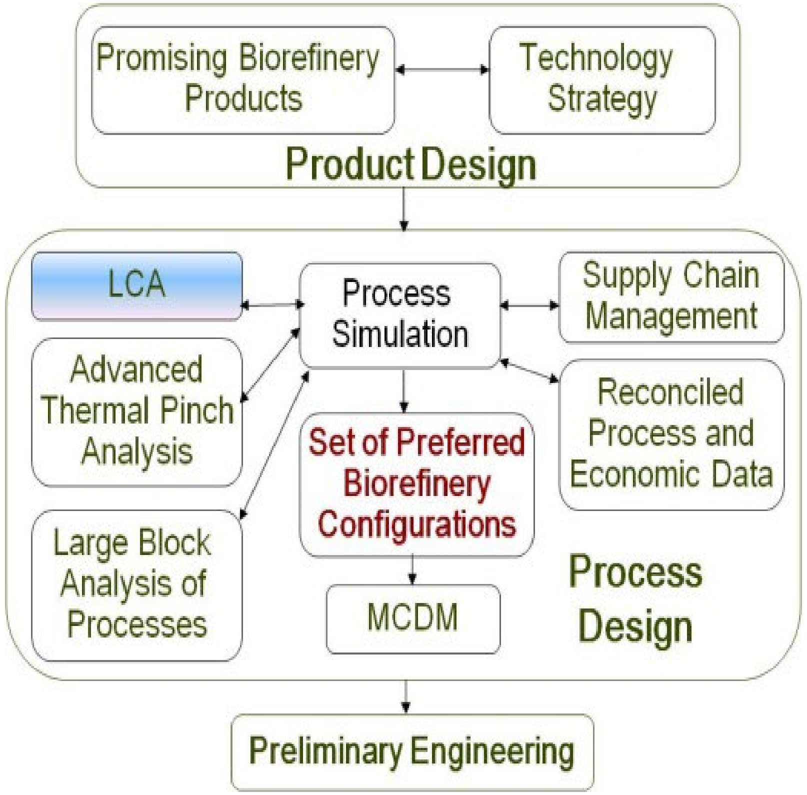
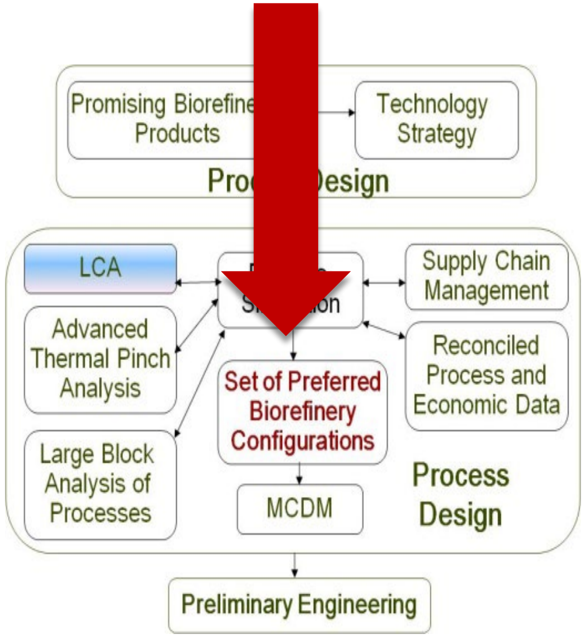


Questions We Have Addressed About LCA Methodology…

- How can we use LCA to compare the environmental impact of **new biorefinery products** with those from **traditional product value chains**?
- How do we systematically adapt LCA methodology to make comparisons considering the **product portfolio**?
- How should **trade-offs** be best considered between different criteria including environmental criteria?
- How should **complex LCA-based environmental impacts** be reflected at the biorefinery decision-making level?

In each case study we address using LCA, how can we interpret LCA results to assist with decision-making?



Some of our LCA-Related Work…

Editorial

Biofpr Biofuels Bioproducts & Biorefining

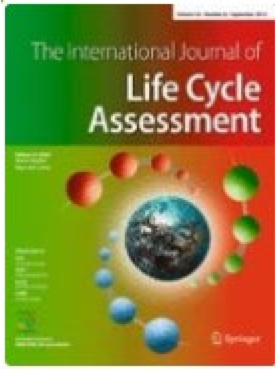
The Potential of Triticale Evaluated by the Power of Engineering and Business Analytics

Int J Life Cycle Assess (2010) 15:198–211
DOI 10.1007/s11367-009-0125-1

PULP AND PAPER

Energy decision making in a pulp and paper mill: selection of LCA system boundary

Caroline Gaudreault · Réjean Samson ·
Paul René Stuart



Appita Peer Reviewed

LCA for the engineering analysis of the forest biorefinery

CAROLINE GAUDREAULT[1], RÉJEAN SAMSON[2], VIRGINIE CHAMBOST[3], AND PAUL STUART[4]

Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

Life cycle assessment of an integrated forest biorefinery: hot water extraction process case study

Banafsheh Gilani,* Paul R. Stuart, École Polytechnique de Montreal, Canada

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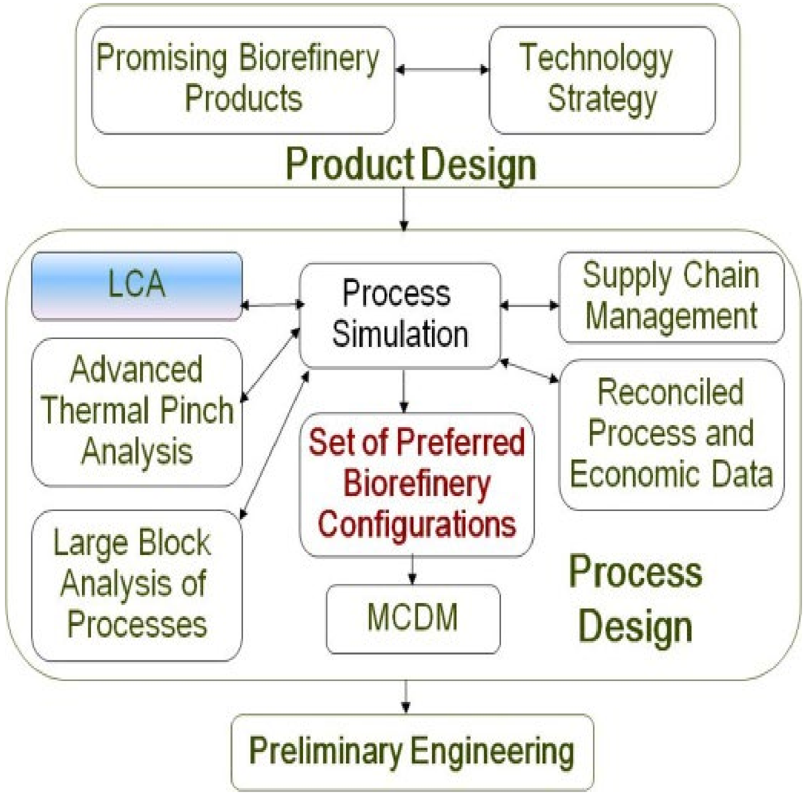


Multi-Criteria Decision-Making (MCDM) Panels: Context

Biorefinery Strategies Assessment

- Biomass Supply
- Technology Assessment and Early Stage Techno-Economics
- Preliminary Market Analysis

Criteria Definition for Sustainable Decision-Making

- Economic Potential
- Risk and Competitiveness
- Environmental Performance

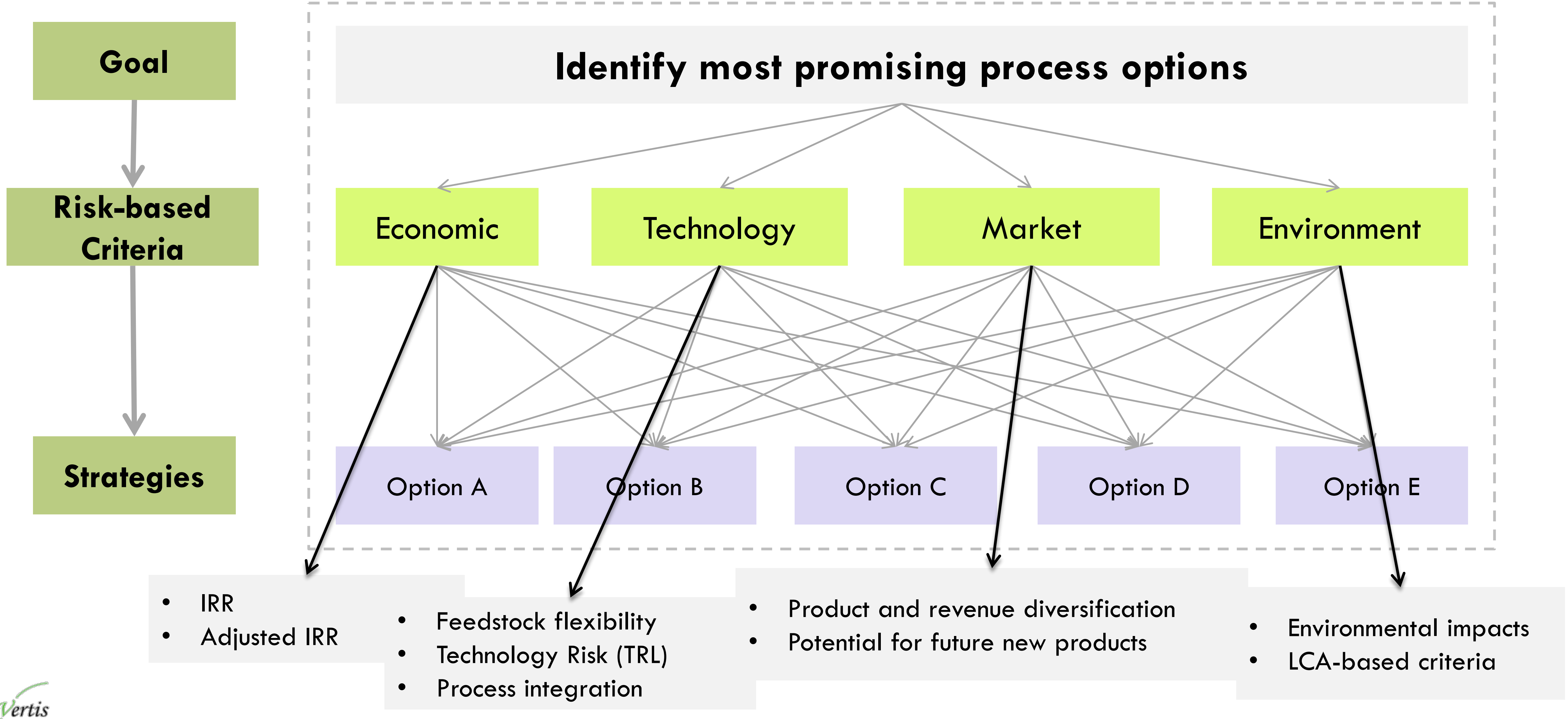
+

+

=

Practical Definition of "Sustainability"

MCDM Panels: Early-Stage Design Decision Criteria

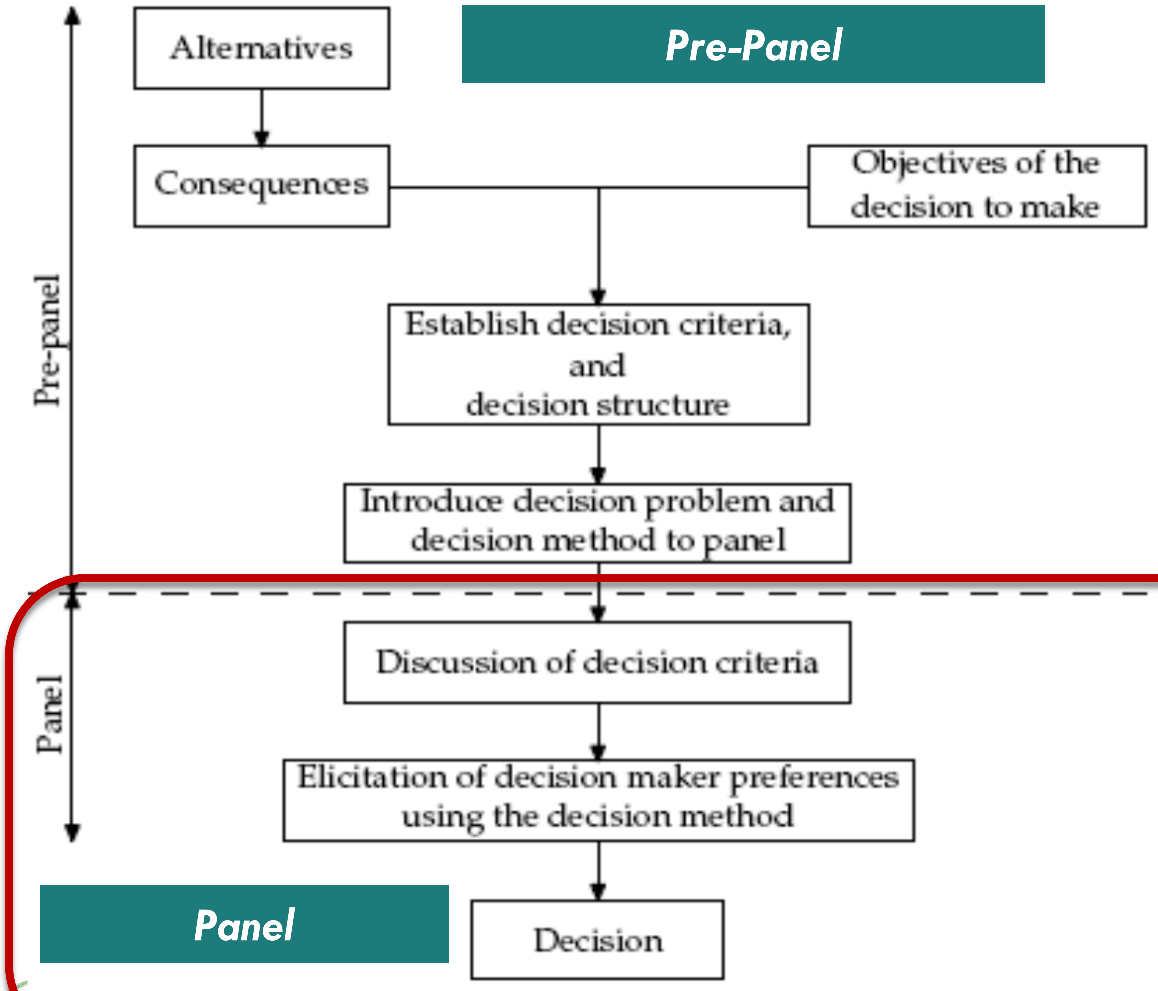


MCDM Panels: Criteria are at the Core of Design Decision-Making

- MCDM criteria should reflect the **diverse values** of the panel participants
- The definition of a "**necessary and sufficient**" set of criteria is initially identified considering company values

- The 6-8 criteria retained for the panel should be **appropriate and representative**
  - **Appropriate:** Taken as a whole, the retained set of criteria represents "**important**" factors that will be assessed by the MCDM panel members
  - **Representative:** The definition/interpretation of criteria should distinguish the candidate strategies under consideration
- The **interpretation** of each criterion should be independent
  - Values of the company are expressed through the interpretation of each criterion during the initial steps of the panel

MCDM Panels: How they Work - Pre-Panel and Panel



Pre-Panel

- → 2 to 3 hour meeting with the panel members – ideally the day prior to the MCDM panel
- → Summarize the ***technology options***, associated ***techno-economic results***, and clarify questions
- → Introduce the ***MCDM criteria*** to the panel members, and their ***preliminary interpretation***

Panel

- → Full-day closed door meeting
- → ***Interpretation*** of evaluation criteria in order to raise awareness of decision-makers about criteria complexity
- → ***Pair-wise comparison*** of the criteria in the context of their results for each option
- → Results presentation/interpretation

MCDM Panels: Activities on Panel Day

1 Criteria Interpretation

- *Connection between criteria definition and impact/implication*
- *Essential activity, so panel members use a similar explicit basis for weighing the criterion, better ensuring consistency*

Alignment on criteria understanding

2 Select the Most Important Criterion and Target Value

- *What is the most important criterion for decision making?*
- *What would be an acceptable value for the most important criterion?*

Consensus on the most important criterion and its target value

3 Criteria Trade-Offs and Justification

- *Trade off between each criterion relative to the most important criterion, considering the context of the calculated results*

Preference elicitation and discussion

4 Results of the Criteria and Solutions Ranking

- *Score of each criterion based on normalized value of each criterion for the options, and their relative weight*
- *Presentation of results and discussion with panel members*

Agreement on Results and their Interpretation

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MCDM Panels: Trading-Off Apples Oranges and Bananas…

This question is asked to each panel member, after identifying IRR as the most important criterion:

IRR = 30% & GHG = 100 MT CO2 eq. /y	=	IRR = how much less than 30%? & GHG = 20 MT CO2 eq./y

IRR=30% & GHG=100 Mt/y

is the same as

IRR=11% & GHG=20 Mt/y

This panel member agrees to ***sacrifice economic performance considerably*** *for improved environmental performance*

GHG reduction is more important for this panel member, when compared to other panel members

IRR=30% & GHG=100 Mt/y

is the same as

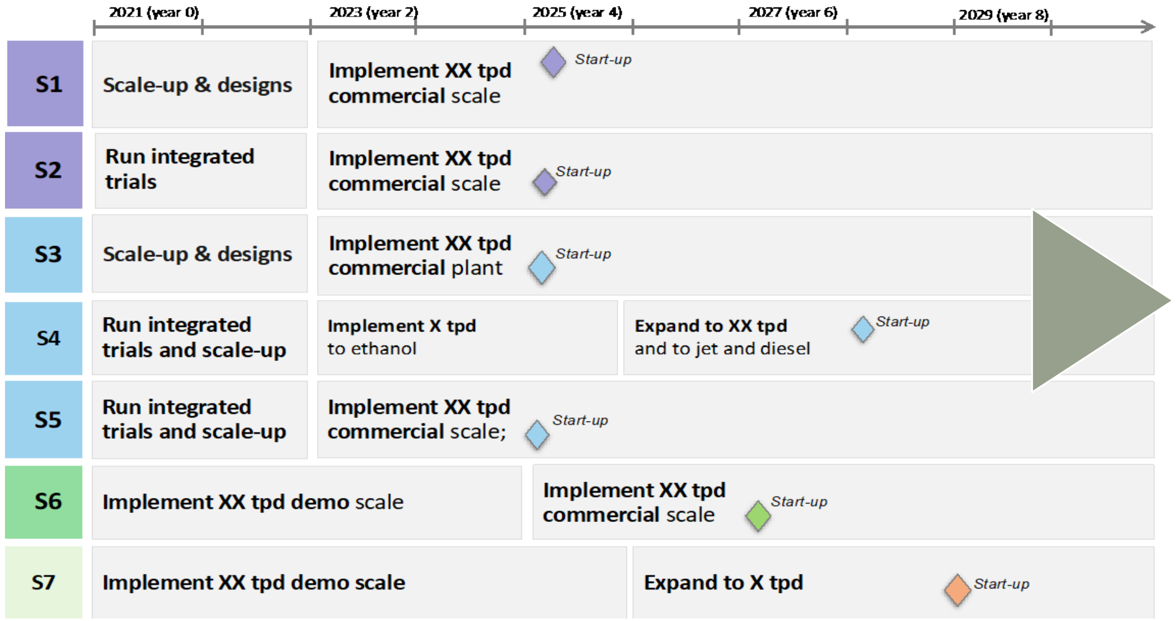
IRR=25% & GHG=20 Mt/y

This panel member agrees to ***some sacrifice*** *in economic performance for improved environmental performance*

MCDM Panels: An example

- Company A would like to invest in renewable fuels production, involving the scaling up of emerging “risky” technologies, while targeting the implementation of multiple large biofuel plants by 2030
  - To identify and implement processes that are economically viable, to generate cash flow for further investments
  - To ensure that preferred strategies meet sustainability targets through their environmental performance

Identify implementation strategies and associated technology risks



Preliminary techno-economics

	S1	S2	S3	S4	S5	S6	S7
Principal product volumes *Phase 2*	*Naphtha: 45 ML/y Diesel: 159 ML/y Oxygen: 280 kt/y*	*Naphtha: 20 ML/y Diesel: 73 ML/y*	*Jet: 84 ML/y Diesel: 9 ML/y*	*Jet: 100 ML/y Diesel: 11 ML/y*	*Jet: 98 ML/y Diesel: 11 ML/y*	*Diesel: 54 ML/y Gasoline: 104 ML/y*	*Lights: 29 ML/y Diesel: 101 ML/y Marine: 74 ML/y*
Overall mass yield to all products; To traffic fuels	*33%; 27%*	*15%; 12%*	*15%; 15%*	*18%; 18%*	*18%; 18%*	*24%; 24%*	*36%; 17%*
Revenues (US$M/a) *Phase 2*	*416*	*191*	*199*	*237*	*209*	*333*	*257*
Operating Costs (US$M/a) *Phase 2*	*203*	*94*	*88*	*85*	*104*	*80*	*91*
EBITDA (US$M/a) *Phase 2*	*213*	*97*	*111*	*152*	*105*	*252*	*166*
Operating Margin *EBITDA/Revenues*	*51%*	*51%*	*56%*	*64%*	*50%*	*76%*	*65%*
Total Capital Costs (incl. WCI) in US$ Million	*1,290*	*1,070*	*890*	*990*	*1,110*	*715*	*900*
Net Present Value @ 8% (US$ M) *All phases*	*160*	*-139*	*4*	*122*	*-162*	*678*	*125*
IRR *All phases*	*10%*	*5%*	*8%*	*11%*	*5%*	*25%*	*12%*

EnVertis

MCDM Panels: An example

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- Preliminary screening of criteria in the context of the project
- Adaptation of criteria retained
- Typically new criteria are defined that reflect unique values

Preliminary triage of criteria bank

Identification and prioritization of MCDM client values/drivers/barriers

- Project constraints
- Perspectives of stakeholders
- Specifics of the set of candidate strategies

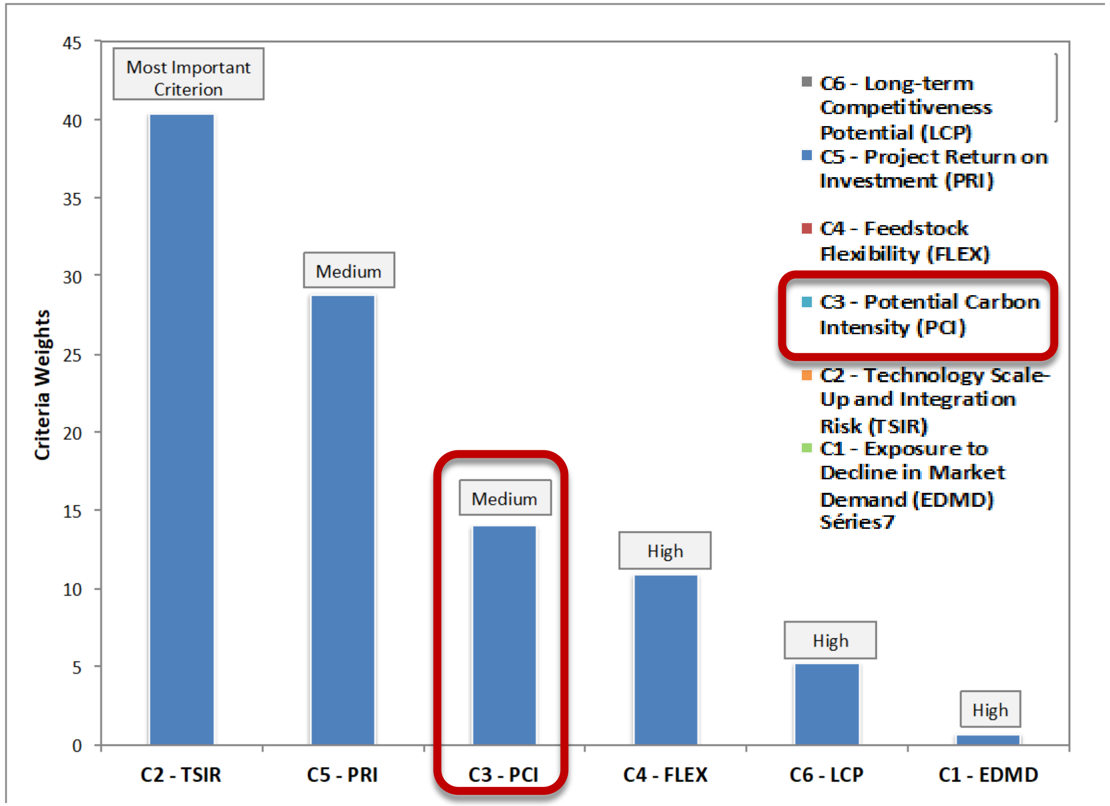
Further Triage of the Set of Criteria

Project Values	Risk/Potential	MCDM Criteria
Market Positioning	*Market Risk*	
Technology Risk and Mitigation	*Technology Risk*	
Sustainability	*GHG Mitigation Potential*	
Market Positioning	*Competitive Advantage*	
Economic Viability	*Economic Risk*	
Scalability	*Scalability Potential*	

Characteristics of MCDM criteria:
- Cover a range of categories
- Are estimates or “surrogates” of perfect values
- Can be quantitative, or semiu-quantitative

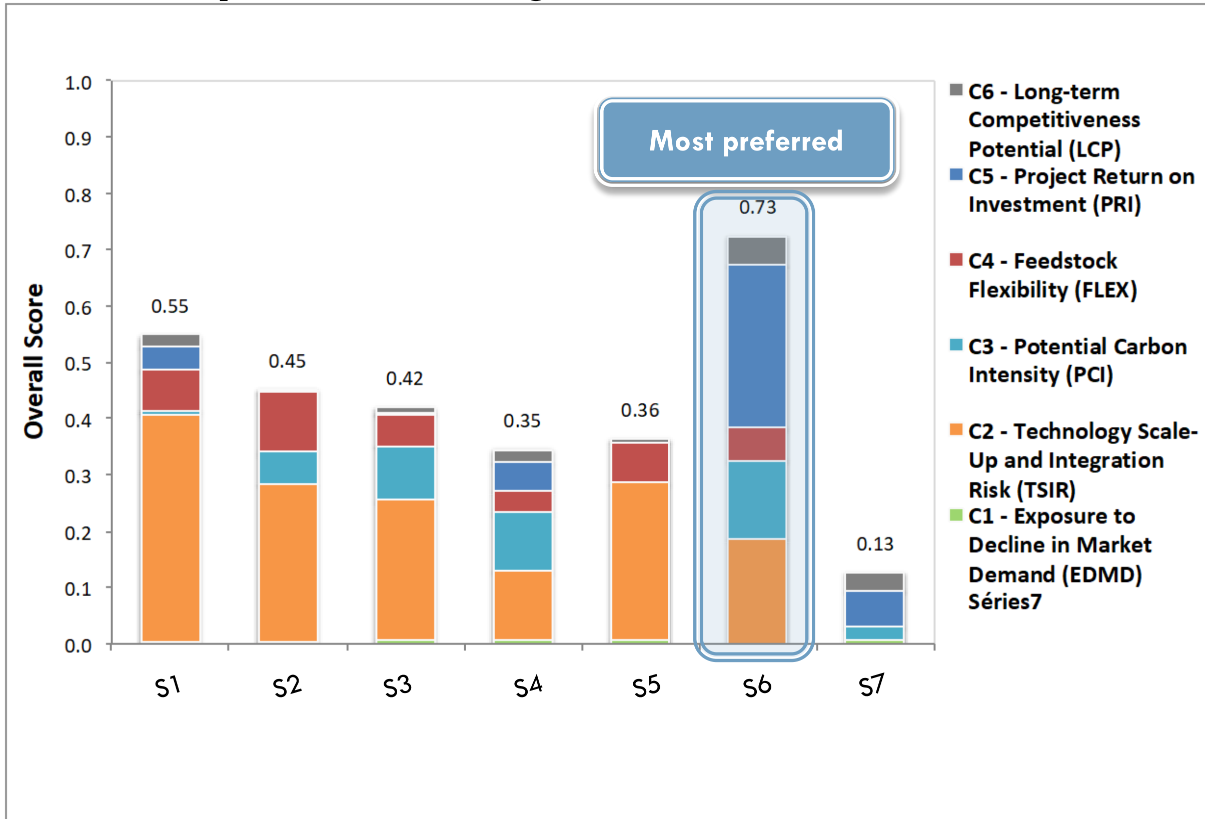
MCDM Panels: An example

Criteria Weighting



Criteria weights are determined by each panel member using the trade-off method

Options Scoring and Prioritization

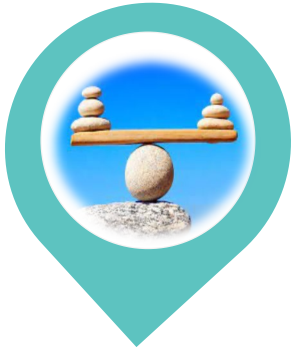


MCDM Results – **prioritization** of “Preferred Solutions”, and alignment between stakeholders

MCDM Panels: What did we learn?

MCDM is an open-ended multi-criteria optimization process that involves project stakeholders, and allows them to express their values in a single day…

→ ***Triage*** of a set of investment options to identify those that are most "preferred"



→ Preferred set of retained options is based on a balanced ***multidisciplinary*** set of considerations, reflected in criteria

→ ***Interpretation*** of the panel outcomes results in ***alignment between panel members,*** and also the ***reasons***

→ ***Technology transfer*** to key decision makers in the company, even if they have not been involved in the day-to-day development of the project

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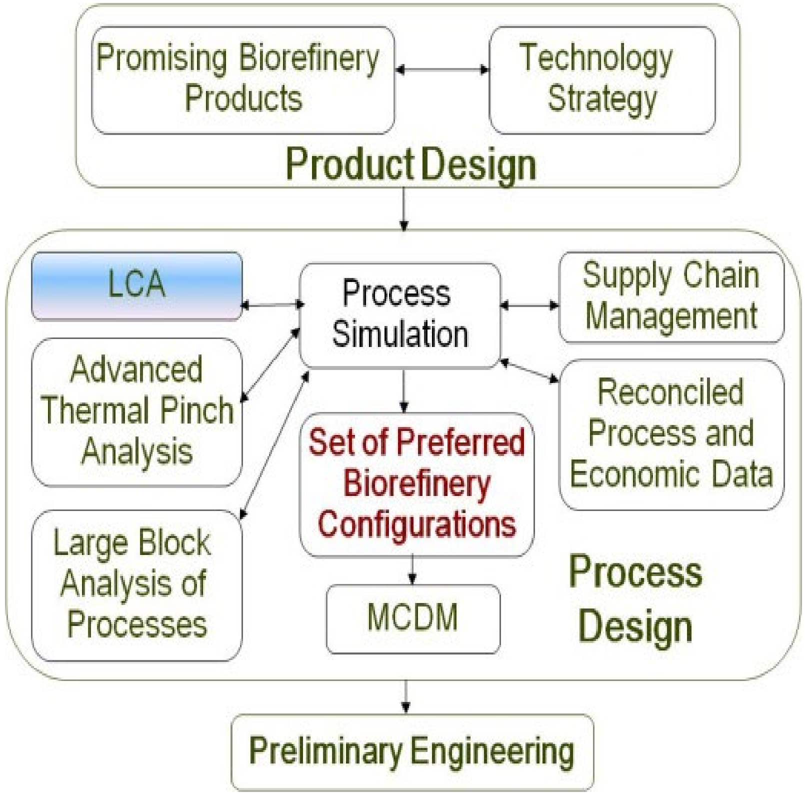
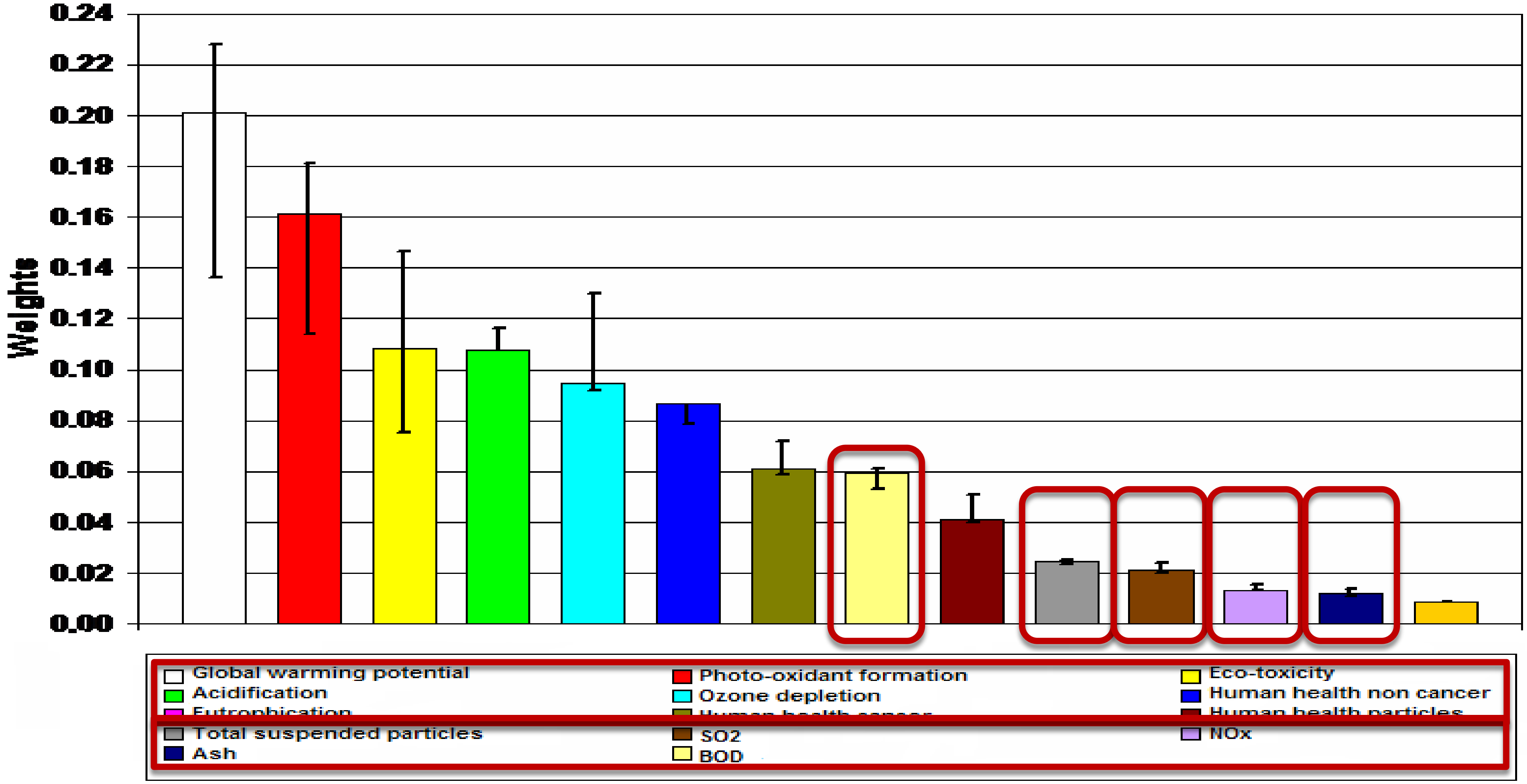


Background on the Nature of Environmental Metrics



Panel evaluating the importance of environmental metrics for the evaluation of project options…

Panel members: NRC, NCASI, CIRAIG, FPI, NGO…

PROCESS DECISION-MAKING EMPHASIZING ENVIRONMENTAL IMPACT:
FAST PYROLYSIS CASE STUDY – PROJECT OBJECTIVES

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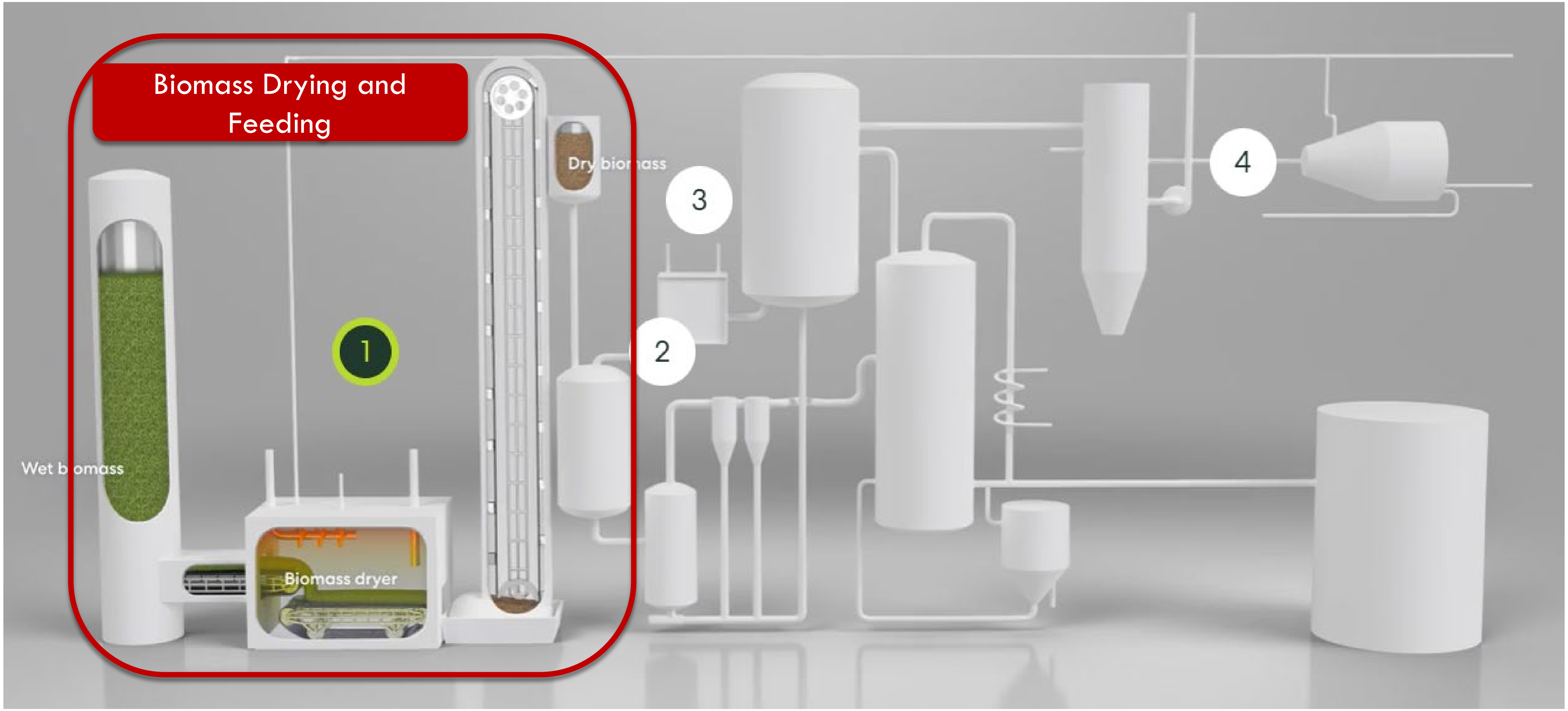
- To identify "winning conditions" for fast pyrolysis implementation in Northern communities, specifically in the context of **Happy Valley-Goose Bay, NL**
    - To identify fast pyrolysis process options that have **"acceptable" economic and environmental performance**
    - To conduct an MCDM with project stakeholders to identify **"preferred"** fast pyrolysis process option(s)
    - *To elaborate particularly on the LCA-derived **environmental criteria** used in the MCDM, so that they are correctly weighted*

Very Very Brief Presentation of Fast Pyrolysis Technology



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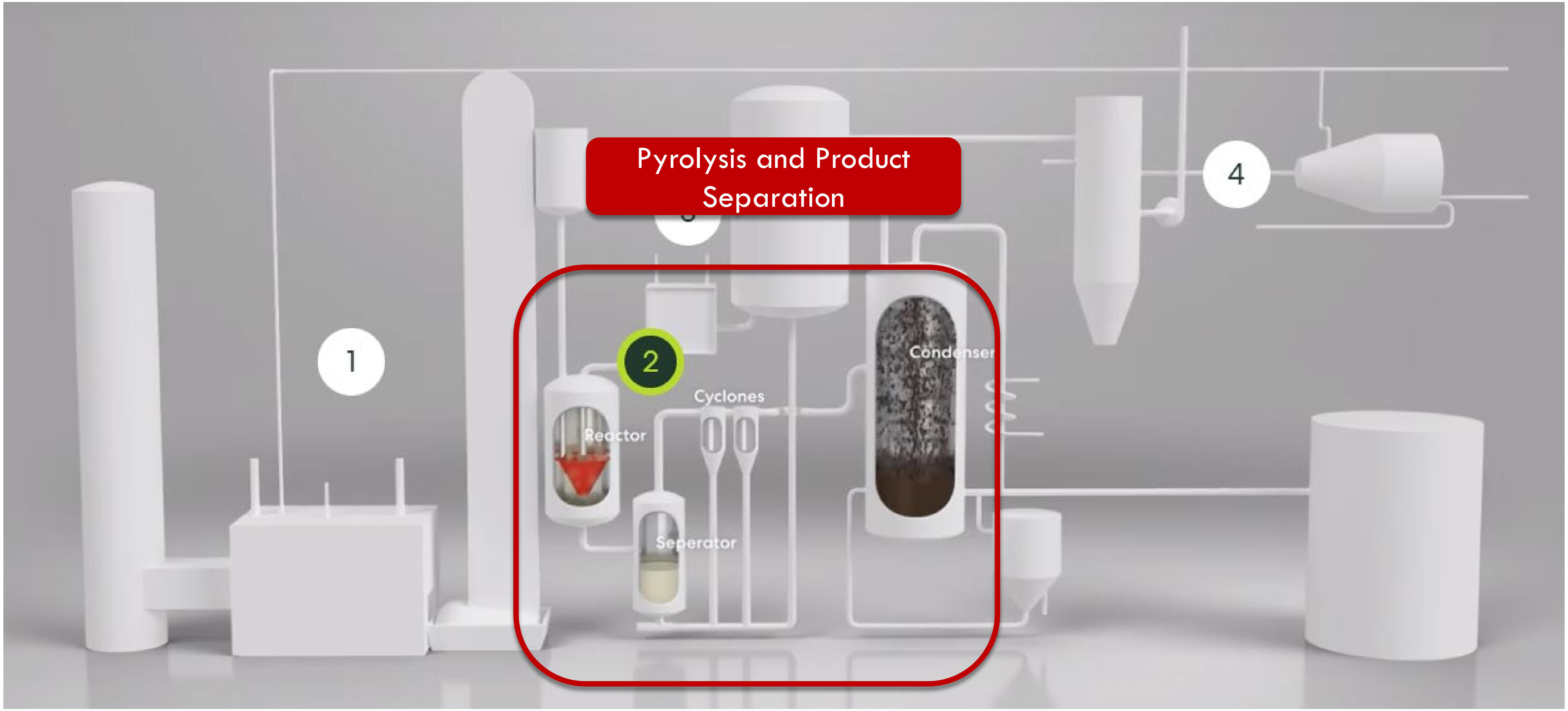

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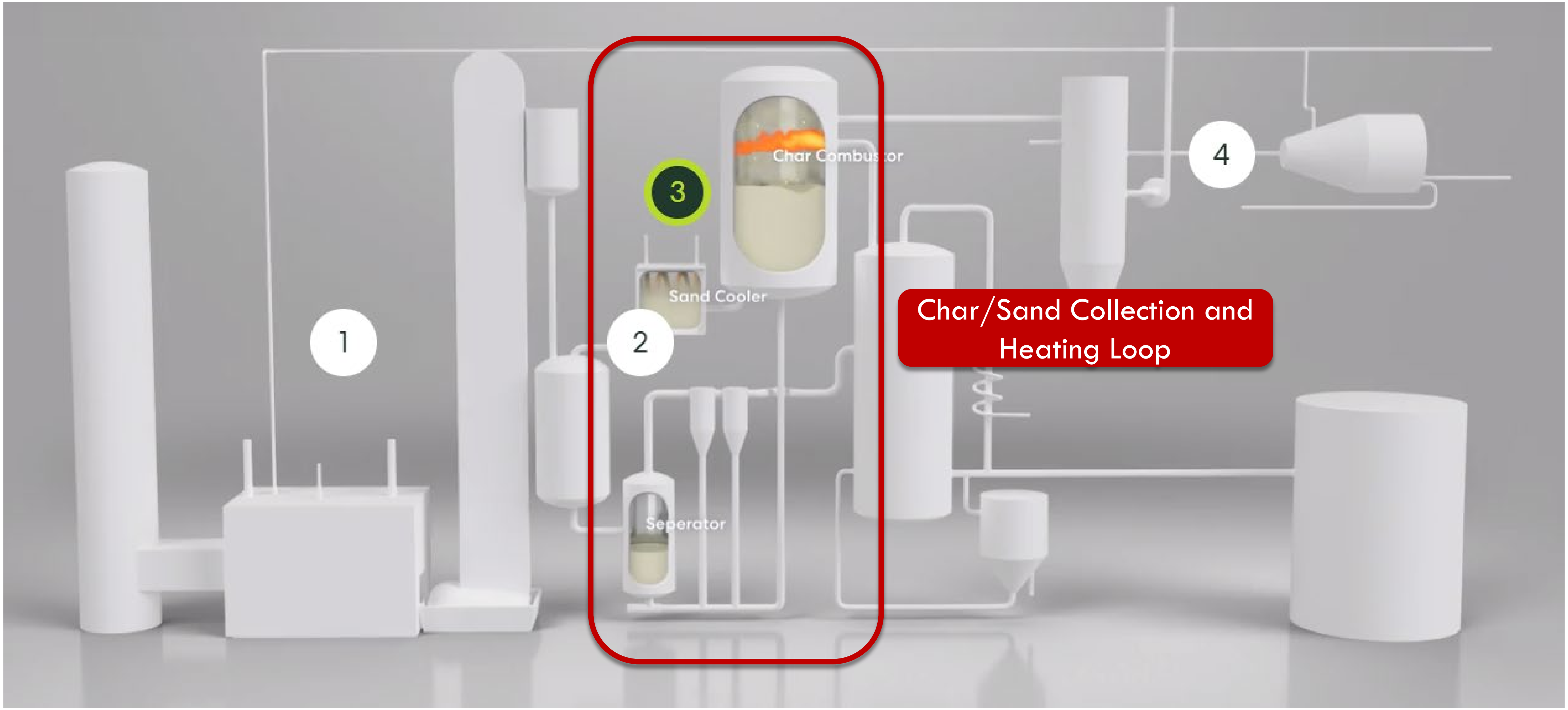

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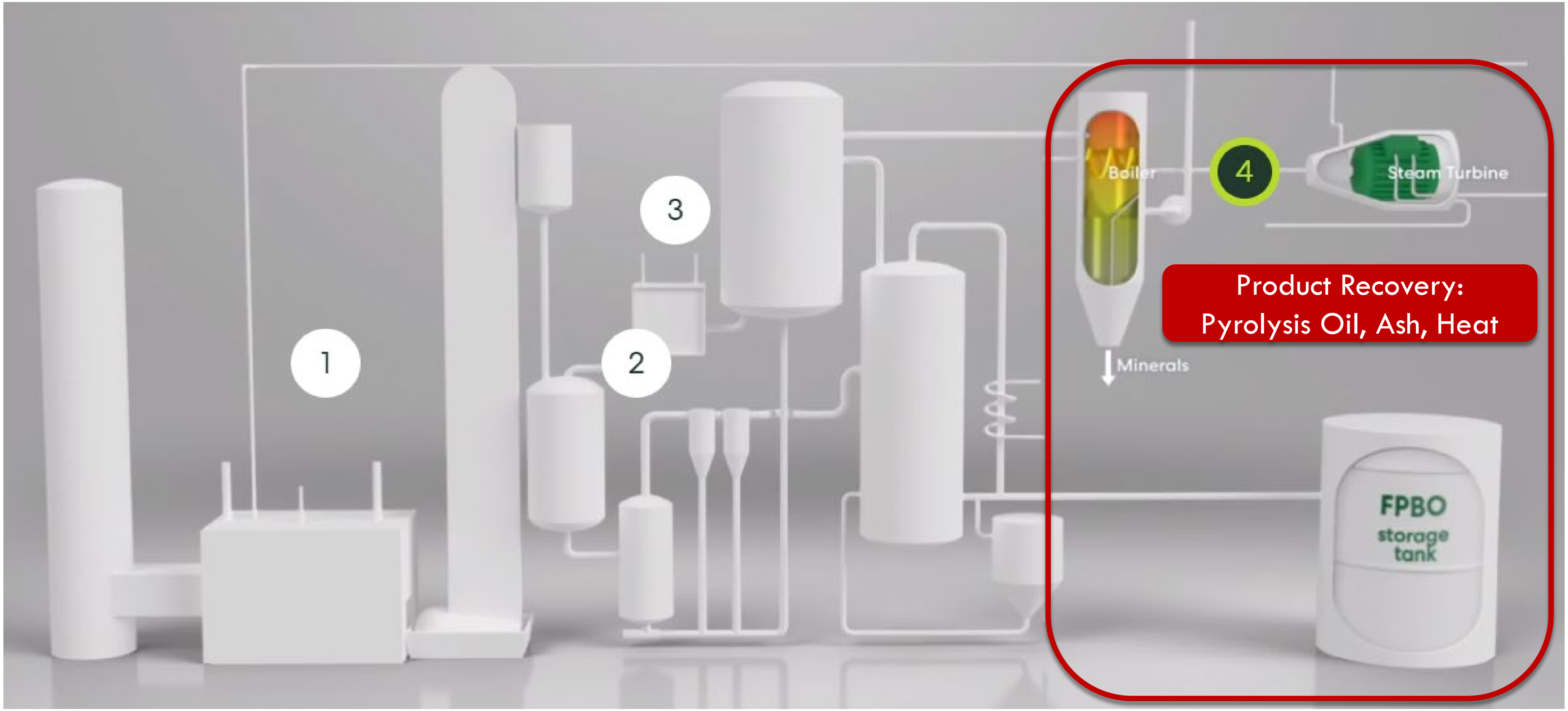
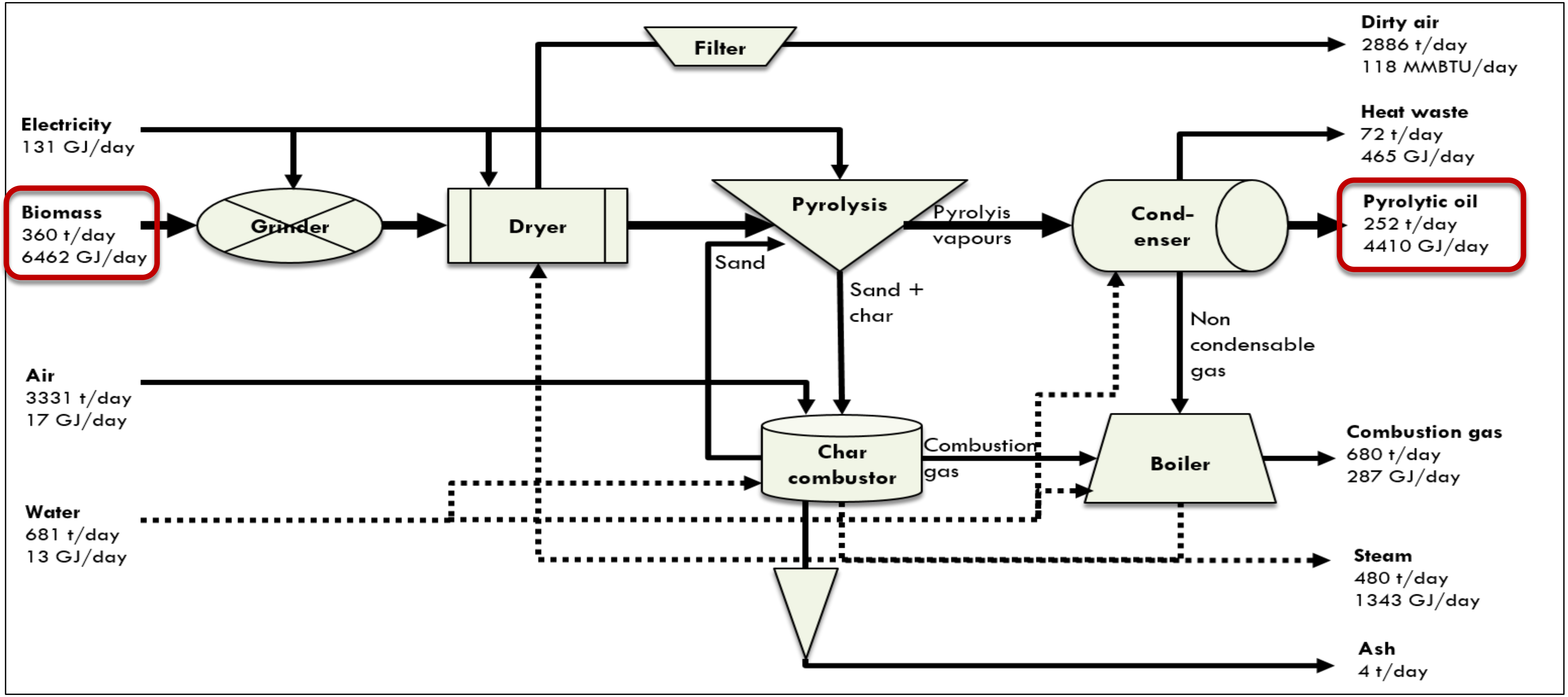
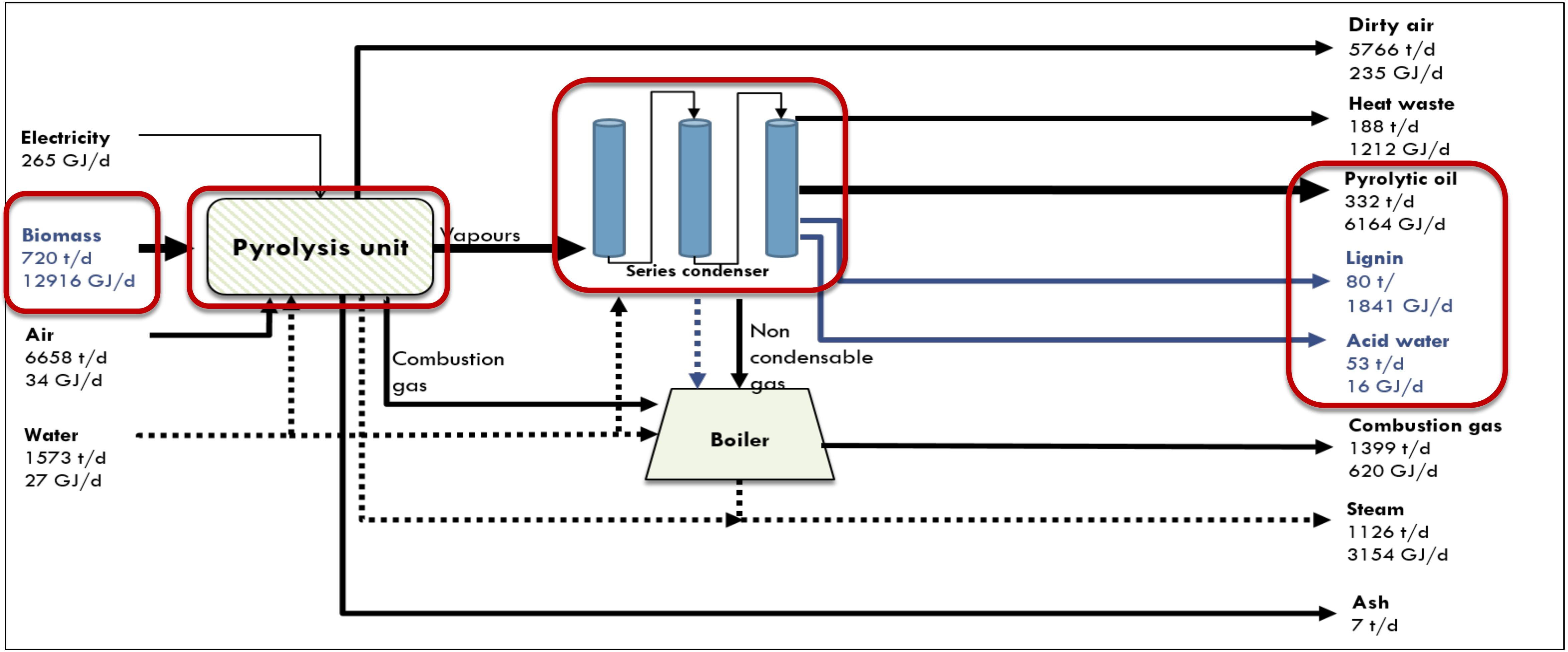


FAST PYROLYSIS "BASE CASE"



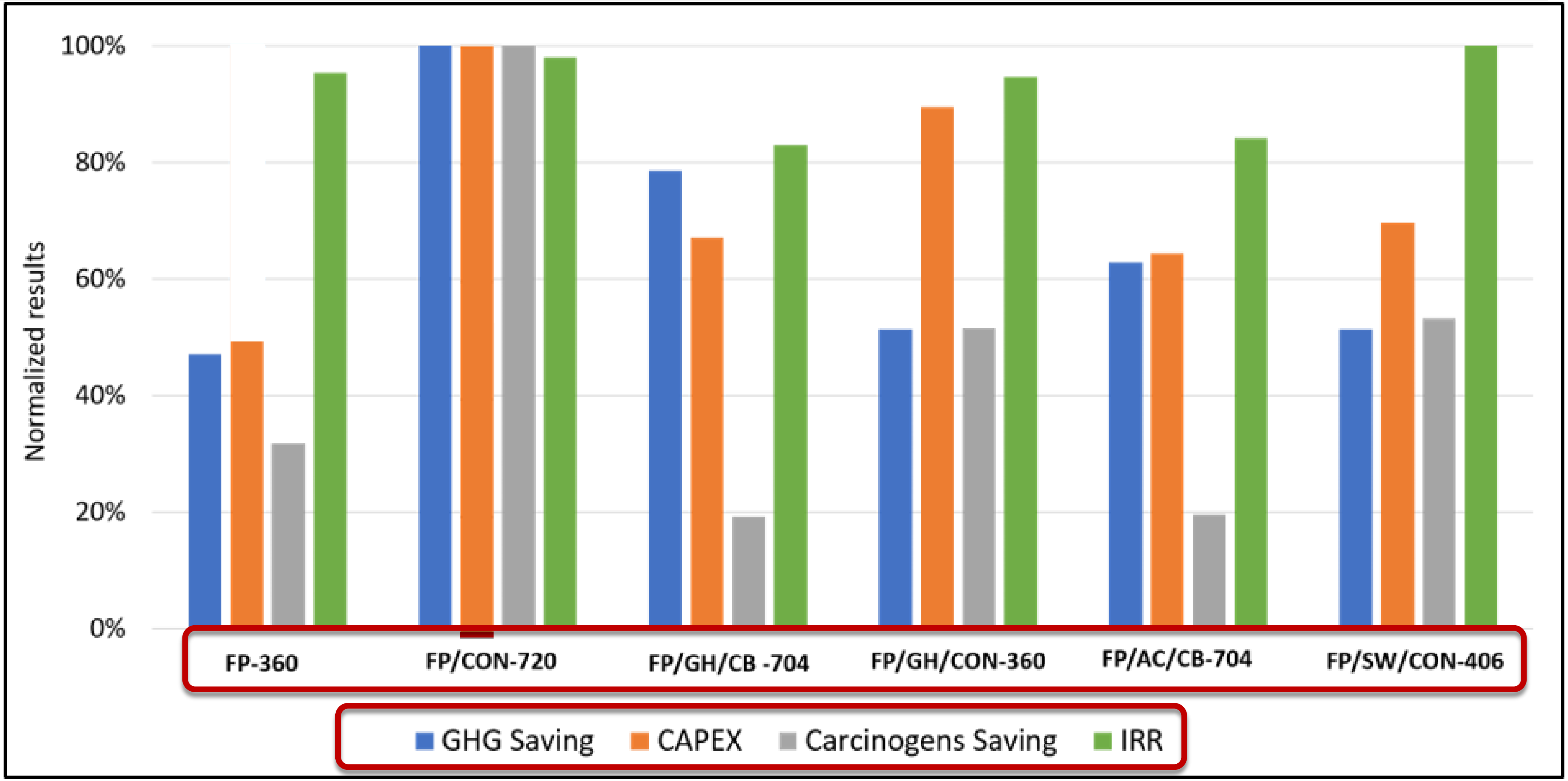
Fast Pyrolysis Option: 2 x Capacity, Progressive Condensation



Fast Pyrolysis Case Study: Process Variants Considered

Process Variant Label	Process Variant	Products in Phase III	Phase I (Years 0-2)	Phase II (Years 3-5)	Phase III (Years 6-26)
FP-360	0. Base Case	Bio-oil, Steam	Pyrolysis (360 bdmt/d)	-	-
FP/CON-720	1.Pyro+, Condensation	Bio-oil with increased LHV (Low Heating Value), steam, lignin		Increase pyrolysis oil capacity (+360 bdmt/d)	Add condensation in series (+0 dbmt/day)
FP/GH/CB-704	2.Pyro, Greenhouse, Carbonization	Bio-oil, vegetables, activated carbon, steam		Add greenhouse (+ 0 bdmt/d)	Add carbonization and Activation (+ 344 bdmt/d)
FP/GH/CON-360	3.Pyro, Greenhouse, Condensation	Bio-oil with increased LHV, vegetables, lignin, steam		Add greenhouse (+ 0 bdmt/d)	Add pyrolysis oil condensation in series (+0 bdmt/d)
FP/CA/CB-704	4.Pyro, Activation, Carbonization	Bio-oil, steam, activated carbon		Add char separation & activation (+ 0 bdmt/d)	Add carbonization (+ 344 bdmt/d)
FP/SW/CON-406	5.Pyro, Sawmill, Condensation	Bio-oil with increased LHV, steam, lumber, lignin		Add sawmill (+46 bdmt/d)	Add condensation in series (+0 bdmt/d)

Fast Pyrolysis Case Study: TEA/LCA Results



Fast Pyrolysis Case Study: MCDM Criteria

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Decision Criterion	Practical Definition	Calculation
IRR: Internal rate of return	Discount rate resulting in a net present value for the project of 0$	$NPV = \sum_{t=0}^{n} \frac{Monetary\ flux}{(1+IRR)^n} = 0$
RUEC: Robustness in unfavorable economic conditions	Monthly earnings before interest and taxes under unfavorable market conditions for 6 months, compared to the total capital cost invested over the 3 project phases	RUEC = monthly EBIT under bad market conditions × 6 months / total capital cost × 100
LSEI: Local socio-economic impact	The direct jobs created at Happy Valley-Goose Bay for each process option	LSEI = Estimate of direct jobs created
AFU: Acceptability of forest use	The proportion of land not used during the project in relation to the total area of forest available for harvesting	AFU = area of forest not affected for the entire project / total area of unprotected forest
PIC: Phased implementation capacity risk	The degree of risk for each process option in terms of maturity, scalability, and implementation capacity (Note.: The operational risk was measured based on the impact from a shutdown and resource demand level for repair)	PIC = 60% × [(50% × near-term scaling factor) + (50% near-term operational risk)] + 40% × [(50% × longer-term scaling factor) + (50% longer-term operational risk)]
DSLE: Development of a sustainable local economy	The potential for creating a sustainable local economy by assessing the potential to attract investors, create new income streams, and penetrate local markets	DSLE = 60% × creation of new revenue streams in near-term local markets + 40% × creation of new income streams in long-term local markets
GHG emissions	The annual potential reduction in greenhouse gas (GHG) emissions associated with biorefinery options in relation to the emissions of the replaced product portfolio	GHG = (GHG emissions from the replaced product portfolio – GHG emissions from the biorefinery portfolio) / GHG emissions from the replaced product portfolio
CT: Carcinogenic toxicity	The annual potential reduction in carcinogenic toxic emissions associated with biorefinery options, compared to the replaced product portfolio	CT = (CT emissions from the replaced product portfolio – CT emissions from the biorefinery portfolio) / CT emissions from the replaced product portfolio

MCDM "PRELIMINARY" CRITERIA INTERPRETATION

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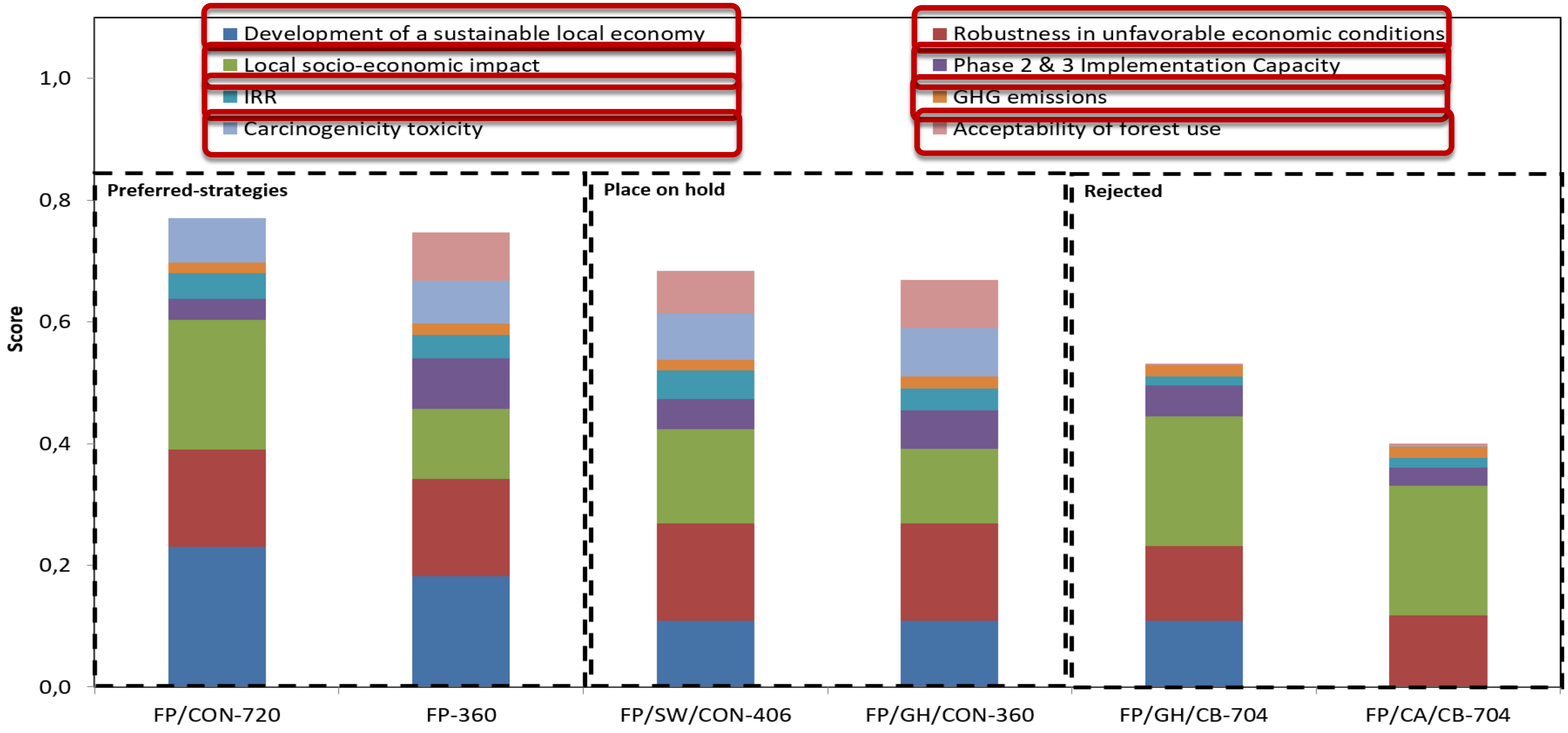
Criteria	Interpretation
IRR (Internal rate of return)	IRR measures the economic benefit (yield) of biorefinery and should be greater than 20%, the minimum acceptable threshold to ensure the profitability of emerging industries in the context of the region.
RUEC (Robustness in unfavorable economic conditions)	The robustness under adverse economic conditions represents the operating margin relative to the worst-case investment in Phase 3, associated in this context with rising biomass prices and fluctuating product prices. If the value of this criterion is greater than 0%, the company will continue its operations.
LSEI (Local socio-economic impact)	The socio-economic impact for the represents a direct and lasting contribution to reducing the unemployment rate. As an example, considering 60% of the working population and a current unemployment rate of 12.7% in Happy Valley-Goose Bay, creation of 100 jobs would reduce this rate by 2 points.
AFU (Acceptability of forest use)	This criterion represents the undeveloped portion of the unprotected forest in the region. A high value of the criterion represents a greater potential for social acceptability of the project.
PIC (Phase 2 & 3 implementation capacity)	This criterion represents the risk associated with technological deployment.
DSLE (Develop sustainable local economy)	Given the high expenditures of the Province of Newfoundland and Labrador on imports, this criterion serves to measure the potential for sustained reductions in expenditures by revenues from local production.
GHG (GHG emissions reduction)	This criterion is used to determine the GHG emissions avoided with the biorefinery plant compared to the replaced product portfolio. For example, a typical 60% decrease for second-generation biofuels is required by the RFS2 program (United States).
CT (Carcinogenic toxicity)	This criterion is used to determine the potential for reducing the impacts on carcinogenic toxicity with the biorefinery plant compared to the replaced product portfolio.

LCA Criteria: GHG Emissions and Carcinogenic Toxicity

- GHG emissions reduction is directly related to GWP, and relative easy to understand by MCDM panelists having a range of related and unrelated LCA expertise – however the range of GHG emissions between the options was not large, lowering its weight
- There was long discussion by the panelists concerning Carcinogenic Toxicity - the panel had difficulty understanding its meaning, as well as the pertinence of the normalized results

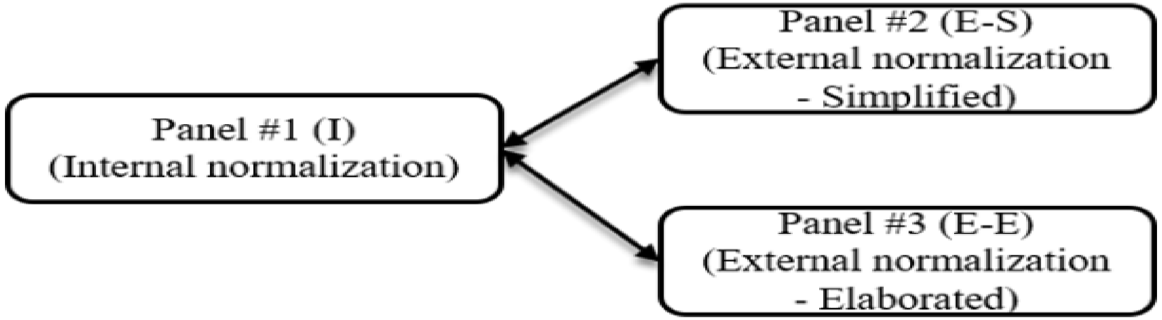
Fast Pyrolysis Case Study: Interpreting the MCDM Results



LCA Criteria: What Can We Do About This Challenge?

- There is a problem with LCA-based criteria – how can we best alleviate this difficulty, even as a compromise but better solution? How can we measure whether "the right" weights have been attributed?

- Let's reconsider how we normalize, and how this impacts the clarity of the interpreted LCA-based criteria…

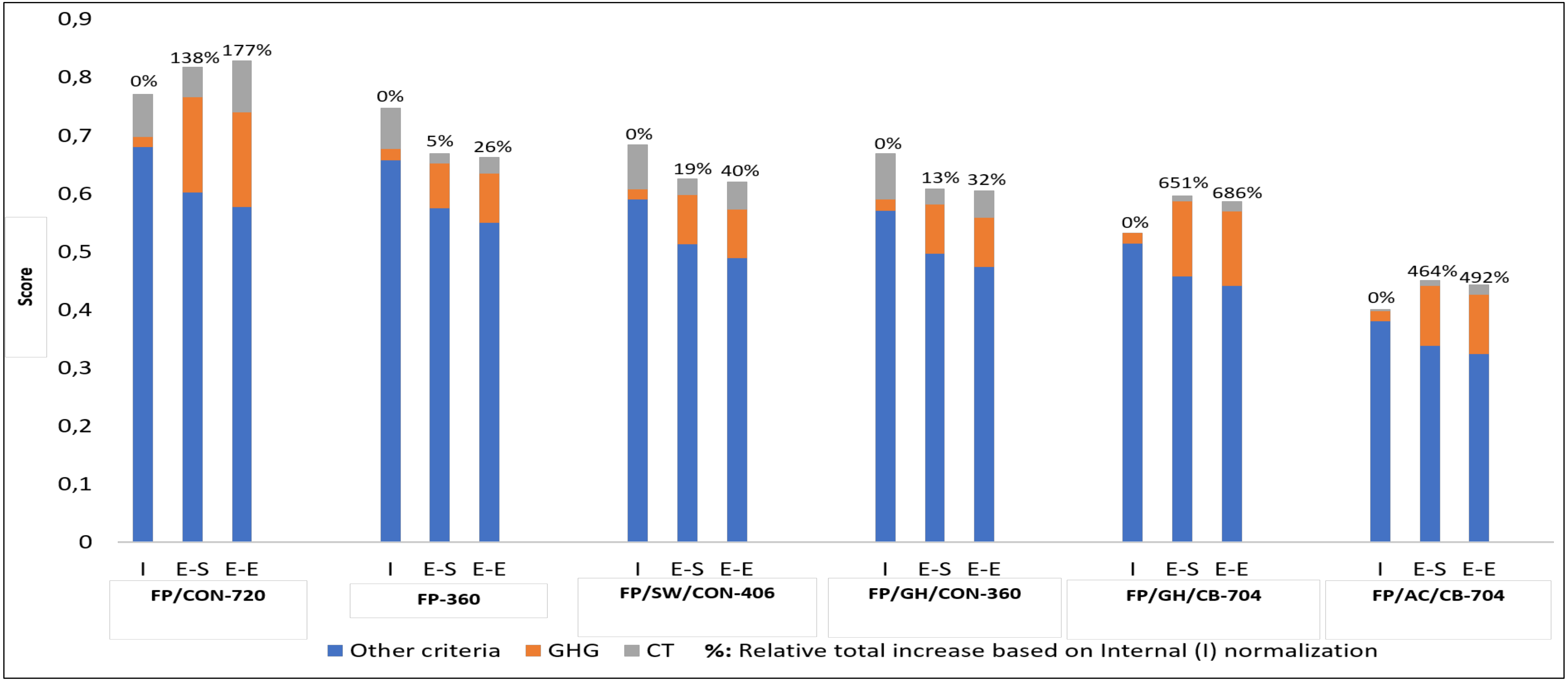


LCA Criteria: Normalization Strategy

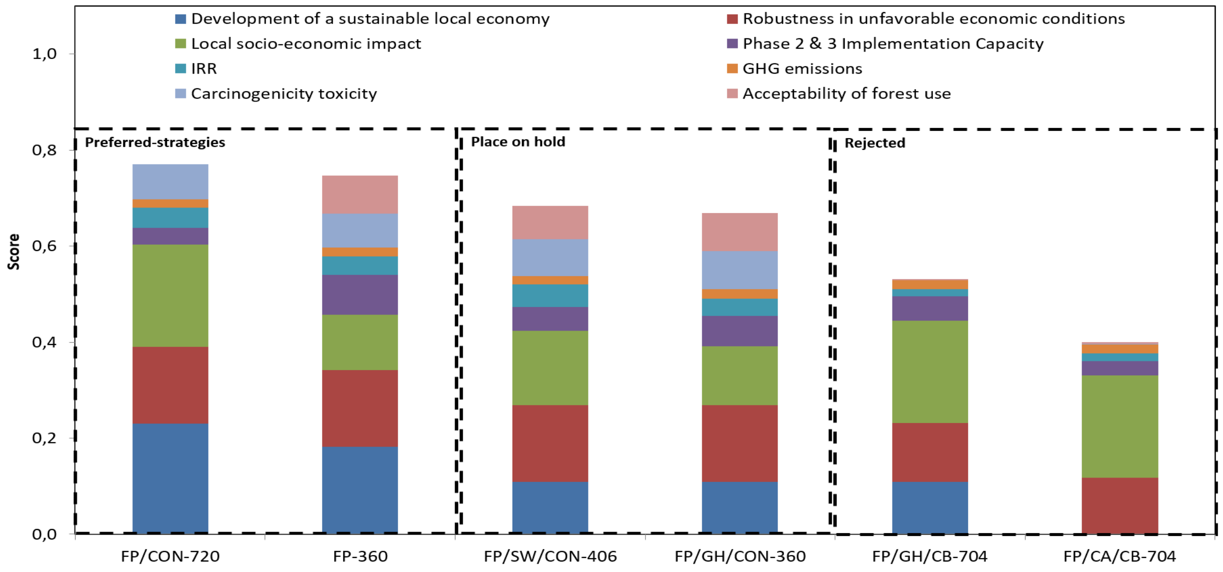
Criterion	Normalization Method	Practical definition – reduction in GHG emissions compared to:	Calculation
GHG emissions	**Internal (I)**	GHG emissions of the replaced product portfolio	GHG = (GHG emissions from the replaced product portfolio – GHG emissions from the biorefinery portfolio) / GHG emissions from the replaced product portfolio
	External-Simplified (E-S)	Total annual GHG emissions in Labrador	GHG = GHG emissions avoided / Total GHG emissions from Labrador
	External-Elaborate (E-E)	Considering emissions from residents of the Province of Newfoundland and Labrador	GHG = Distance between [2 tonnes per CO_2/inhabitant] and [Annual GHG reduction / Number of inhabitants in NL]

Criterion	Normalization Method	Practical definition - reduction in carcinogenic toxic emissions compared to:	Calculation
CT (Carcino-genic toxicity)	**Internal (I)**	Carcinogenic emissions of the replaced product portfolio.	CT = Carcinogenic toxic emissions avoided annually / Carcinogenic toxic emissions from the replaced product portfolio
	External-Simplified (E-S)	The annual years lost to cancer in Happy Valley-Goose Bay	CT = Years of life not lost with carcinogenic emissions (DALY) / Years of life annually lost due to cancer in Happy Valley-Goose Bay N.B. DALY stands for disability-adjusted life years.
	External-Elaborate (E-E)	This criterion measures the reduction in years of life lost	TC = [(Years of lost life avoided by CT emissions per year / (Newfoundland and Labrador inhabitants)] / [(Years of life lost (consumption patterns in Canada per year) / Inhabitants of Canada)]

LCA Criteria: Impact of External Normalization

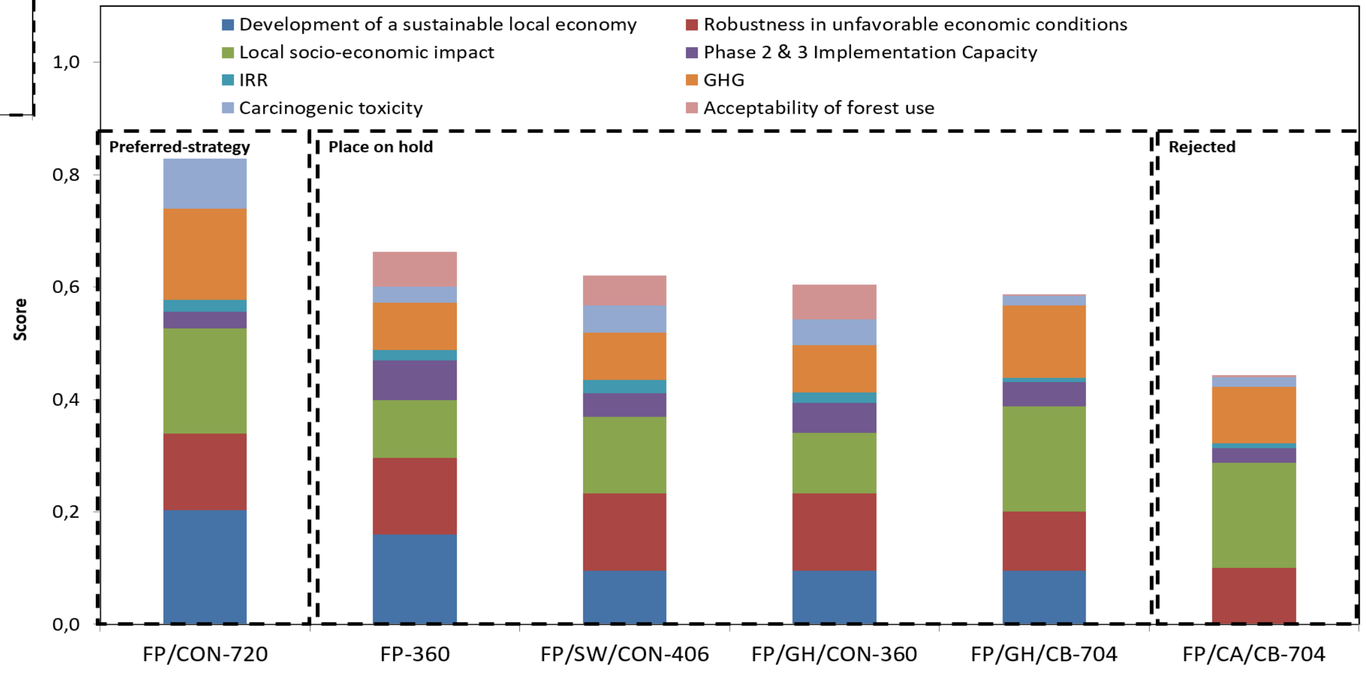


CASE STUDY: MCDM RESULTS WITH EXTERNAL NORMALIZATION



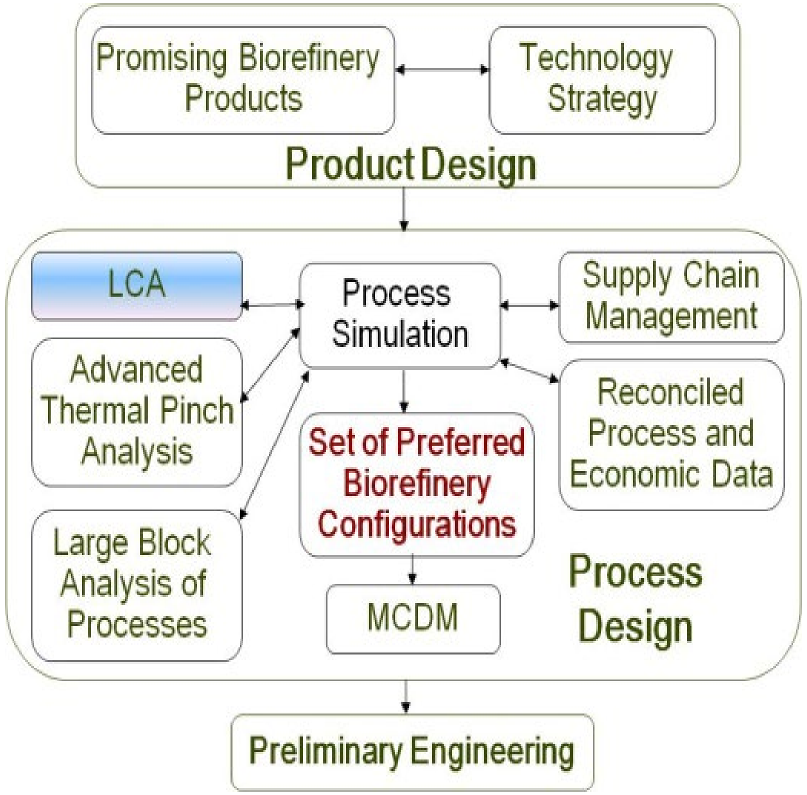
Internal Normalization of LCA impact criteria

External Normalization of LCA impact criteria

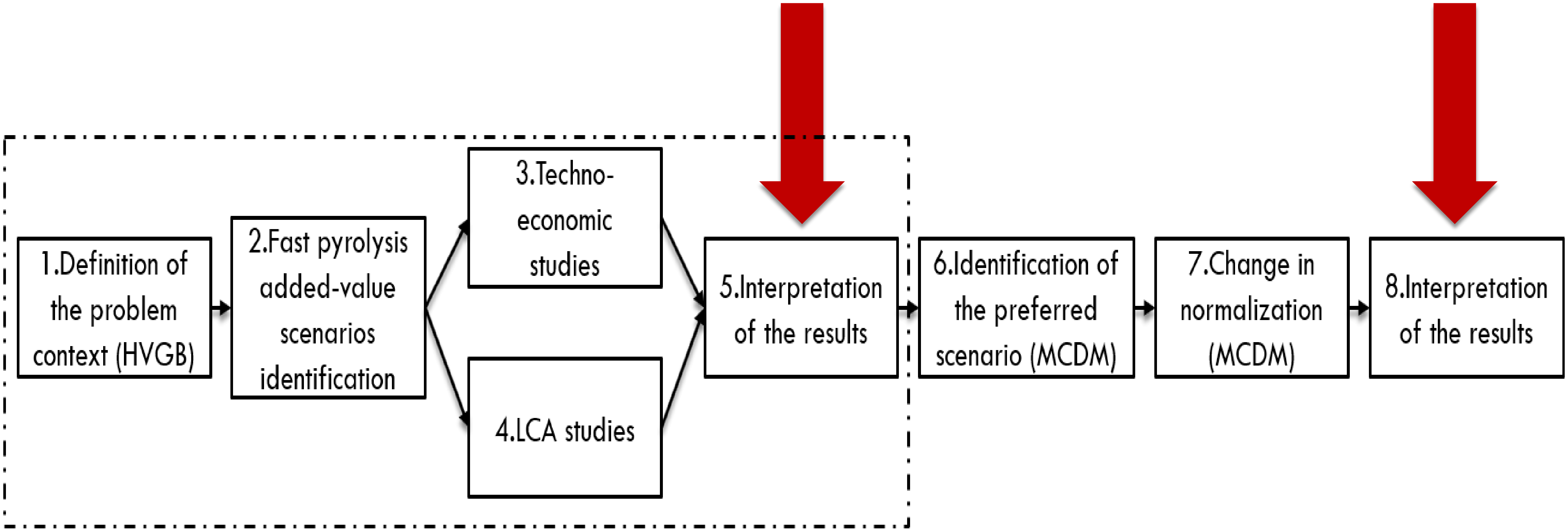


Lecture Outline

- A **very very brief history** of LCA from the perspective of **design decision-making**
- Some **methodological questions** related to LCA and design decision-making that we have addressed in our research program over the years
- **Design decision-making, MCDM panels, and LCA-based environmental criteria**
- A **case study**, and **interpreting LCA results** for design decision-making
- **Ongoing research activities** and **take-home messages**



Summary of Our Fast Pyrolysis Case Study…



Take-Home Messages

- Life Cycle Design is increasingly common today
- While a powerful concept, LCA and Life Cycle design must be placed into the overall context of design decision-making in order to influence outcomes…
  - Multi-Criteria Decision-Making (MCDM) panels assist in understanding the decision-makers, and creating alignment between decision-making stakeholders
  - Criteria selection is critical: Ideally the sustainability context is reflected in MCDM criteria
  - Weights are determined for (1) the criteria, and (2) criteria values for the options being compared – and reflect the values of the MCDM panel members
- LCA-based environmental criteria are important for design, and especially, should be considered in early-stage design
  - As calculated, LCA-based criteria are difficult to interpret, and thus often result in low weights – the exception being GHG emissions reduction
  - Through external normalization methods, LCA-based criteria can be more understandable to MCDM panel members, increasing the weights of environmental impact criteria

BEST 402 Industrial Ecology – Professor Qingshi Tu

Interpreting Life Cycle Assessment (LCA) Results

Case Study: Fast Pyrolysis of Forest Biomass

Thank You – Merci!