Algae based biorefineries: boon or bane?

Lessons learnt from a decade of research and demonstration units worldwide

Dr Guido Reinhardt & Marie Hemmen

5th Latin American Congress on Biorefineries
from laboratory to industrial practice
January 7-9, 2019 – Concepción, Chile

Who we are – What we do

IFEU - Institute for Energy and Environmental Research Heidelberg, since 1978

- Independent scientific research institute
- Organised as a private non profit company with currently about 70 employees
- Research / consulting on environmental aspects of
  - Energy (including Renewable Energy)
  - Transport
  - Waste Management
  - Life Cycle Analyses
  - Environmental Impact Assessment
  - Renewable Resources
  - Environmental Education

Who we are - What we do

IFEU focuses regarding the topic of biomass

- Research / consulting on environmental aspects of
  - transport biofuels
  - biomass-based electricity and heat
  - biorefinery systems
  - biobased materials
  - agricultural goods and food
  - cultivation systems (conventional agriculture, organic farming, etc.)
- Potentials and future scenarios
- Technologies / technology comparisons
- CO_2 avoidance costs
- Sustainability aspects / valuation models

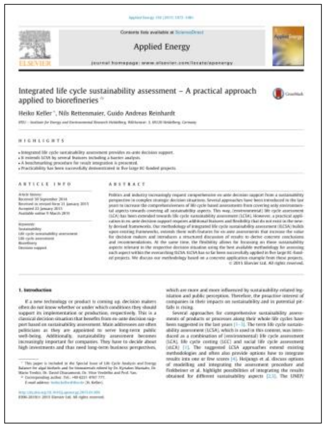
Who we are - What we do

IFEU - Institute for Energy and Environmental Research Heidelberg, since 1978

- **Our clients (on biofuel/biomass studies)**
  - World Bank
  - UNEP, GIZ, UNIDO, FAO, UNFCCC etc.
  - European Commission, IEA
  - National and regional Ministries
  - Associations (national and international)
  - Local authorities
  - WWF, Greenpeace, Friends of the Earth etc.
  - Companies (DaimlerChrysler, German Telekom, etc.)
  - Foundations (German Foundation on Environment, British Foundation on Transport etc.)

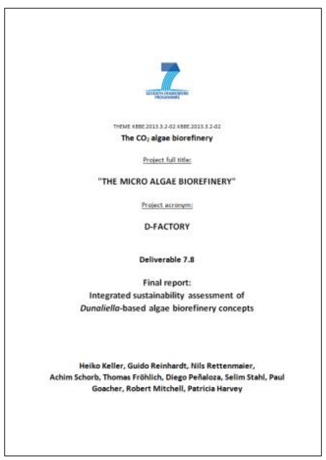
Background

IFEU: Projects and publications on algae based products (selection)


Applied Energy

Integrated life cycle sustainability assessment – A practical approach applied to biorefineries

Heiko Keller, Nils Rettenmaier, Guido Andreas Reinhardt


THEME KBBE.2013.3.2-02 KBBE.2013.3.2-02

The CO_2 algae biorefinery

Project full title:

"THE MICRO ALGAE BIOREFINERY"

Project acronym:

D-FACTORY

Deliverable 7.8

Final report:

Integrated sustainability assessment of *Dunaliella*-based algae biorefinery concepts

Heiko Keller, Guido Reinhardt, Nils Rettenmaier, Achim Schorb, Thomas Fröhlich, Diego Peñaloza, Selim Stahl, Paul Goacher, Robert Mitchell, Patricia Harvey

H. Keller, N. Rettenmaier, G. A. Reinhardt (2018): How to set up sustainable algae biorefineries – learning from algae based nutraceuticals. Proceedings of the „26th EU Biomass Conference & Exhibition“, May 16, 2018, Copenhagen, Denmark

H. Keller, N. Rettenmaier G. Reinhardt: Designing sustainable algae biorefineries. Biobased Future, Nr. 9, 2018, p17

H. Keller, S. Gärtner, G. A. Reinhardt, N. Rettenmaier (2017): Environmental assessment of Dunaliella-based algae biorefinery concepts. In: D-Factory project reports, supported by the EU`s FP7 under GA No. 613870, IFEU – Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany

H. Keller, G. A. Reinhardt, S. Gärtner, N. Rettenmaier, P. Goacher, R. Mitchell, D. Peñaloza, S. Stahl, P. Harvey **(2017): Integrated sustainability assessment of Dunaliella-based algae biorefinery concepts**. In: D-Factory project reports, supported by the EU`s FP7 under GA No. 613870, IFEU – Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany

H. Keller, G. A. Reinhardt, N. Rettenmaier, A. Schorb, M. Dittrich (2017): Environmental assessment of algae-based PUFA production. In: PUFAChain project reports, supported by the EU's FP7 under GA No. 613303, IFEU – Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany

H. Keller, N. Rettenmaier, A. Schorb, M. Dittrich, G. A. Reinhardt *et al.* (2017): Integrated sustainability assessment of algae-based PUFA production. In: PUFAChain project reports, supported by the EU's FP7 under GA No. 613303, IFEU – Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany

G. A. Reinhardt, H. Keller (2017): LCA of algae based biorefineries: actual state of the art worldwide and perspectives. Proceedings of the 13th International Conference on Renewable Resources and Biorefineries, Wroclaw, Poland, 7 – 9 June, 2017. http://www.rrbconference.com/rrb-13-welcome

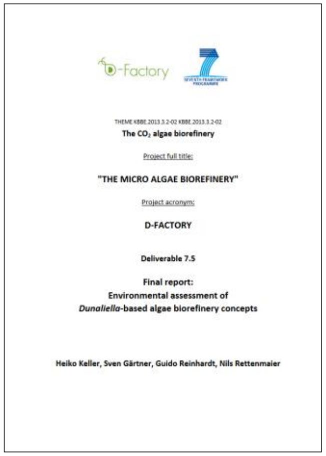
S. Gärtner, H. Keller, G. A. Reinhardt, N. Rettenmaier (2017): The top 5 options to make algae products more sustainable: lessons learnt from recently completed studies in Europe. Proceedings of the Algae Biomass Summit 2017, Salt Lake City, USA, 29 October – 1 November, 2017. http://www.algaebiomasssummit.org/

H. Keller, N. Rettenmaier, G.A. Reinhardt (2015): Integrated life cycle sustainability assessment – A practical approach applied to biorefineries. Integrated life cycle sustainability assessment – A practical approach applied to biorefineries. Applied Energy, Vol. 154, pp. 1072 – 1081

Cont. next slide →

Background

IFEU: Projects and publications on algae based products (selection)


D-Factory

THEME KBBE.2013.3.2-02 KBBE.2013.3.2-02
The CO_2 algae biorefinery
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Deliverable 7.5
Final report:
Environmental assessment of
Dunaliella-based algae biorefinery concepts

Heiko Keller, Sven Gärtner, Guido Reinhardt, Nils Rettenmaier


Deliverable 9.5
Final report: Integrated sustainability assessment
of algae-based PUFA production

G. A. Reinhardt (2014): **Wie grün sind Algen? Ein Überblick aus Nachhaltigkeitssicht (How green are algae? Assessing sustainable development of algae production).** Proceedings of the „1. Bioökonomie-Kongress Baden-Württemberg", Stuttgart, Germany, 29 – 30 October, 2014

G. A. Reinhardt, C. Cornelius (2014): **Algal biomass use: an integrated assessment of its sustainability with LCA as starting point.** Proceedings of the Algae Biomass Summit 2014, San Diego, USA, 29 September – 3 October, 2014

P.J. Harvey, **G. A. Reinhardt and 17 co-authors (2014): The CO_2 Microalgae Biorefinery: High value products from low value wastes using halophylic microalgae in the D-Factory.** Part 1: Tackling cell harvesting. Proceedings of „22nd European Biomass Conference and Exhibition", Hamburg, Germany, June 23 – 26, 2014

G. A. Reinhardt (2014): **Conclusive Sustainability Assessment of Algal Biomass Pathways through Considerable Extension of LCA Application**. 22nd EU BC&E Algae event, Hamburg, Germany, 25 June, 2014

G. A. Reinhardt (2014): **How to extend an LCA of algal biomass pathways to a conclusive sustainability analysis**. Proceedings of the „4th International Conference on Algal Biomass, Biofuels & Biomaterials", Santa Fe, USA, June 15 – 18, 2014

A. Kryvenda, S. Durm, **G. A. Reinhardt**, T. Friedl **(2014)**: **The PUFAChain project: a value chain from algal biomass to lipid-based products**. Proceedings of the "7. Bundesalgenstammtisch", Köthen, Germany, 3 – 4 June, 2014

G. A. Reinhardt (2014): **PUFAChain: the value chain from microalgal diversity to PUFAs: technological, environmental and integrated sustainability assessments**. Proceedings of the 2nd European Workshop „Life Cycle Analysis of Algal based Biofuels and Biomaterials", Brussels, Belgium, 24 April, 2014

P.J. Harvey, **G. A. Reinhardt** and 14 co-authors **(2012)**: **Glycerol production by halophytic microalgae strategy for producing industrial quantities in saline water.** Proceedings of the „20th EU Biomass Conference & Exhibition", June 18 – 22, 2012, Milan, Italy, pp 85 – 90

P.J. Harvey, **G. A. Reinhardt** and 12 co-authors **(2012)**: **Glycerol Production by Novel Strains of Dunaliella and Asteromonas: Basis for producing industrial quantities of glycerol in highly saline water**. Proceedings of the „20th EU Biomass Conference and Exhibition", Milan, Italy, June 18-22, 2012

Downloads from **www.ifeu.de/algae**

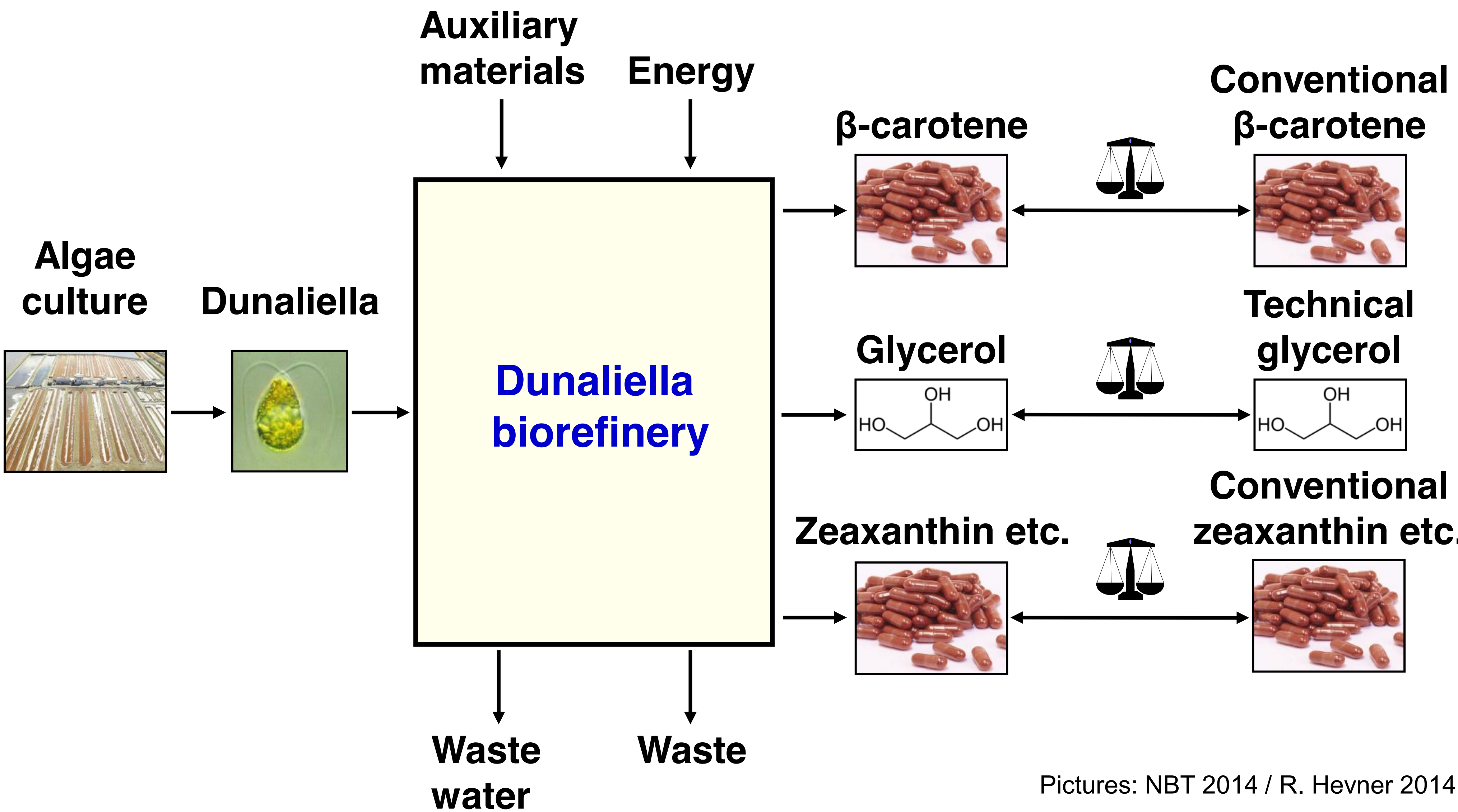
Background: D-Factory project

Call	KBBE.2013.3.2-02: The Micro Algae Biorefinery
Project title	**D-Factory – The Micro Algae Biorefinery**
Grant Agreement No.	613870
Duration	48 months
Start	1st December 2013
End	30th November 2017
No. of participants	13 partners from 8 different countries
Total estimated costs	10,083,863.00 Euro
Total EU contribution	7,177,440.00 Euro

Hafren Investments

Background: D-Factory project

Algae based biorefinery of tomorrow



Pictures: NBT 2014 / R. Hevner 2014

Algae Production: photo-bio-reactors

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Algae Production: photo-bio-reactors

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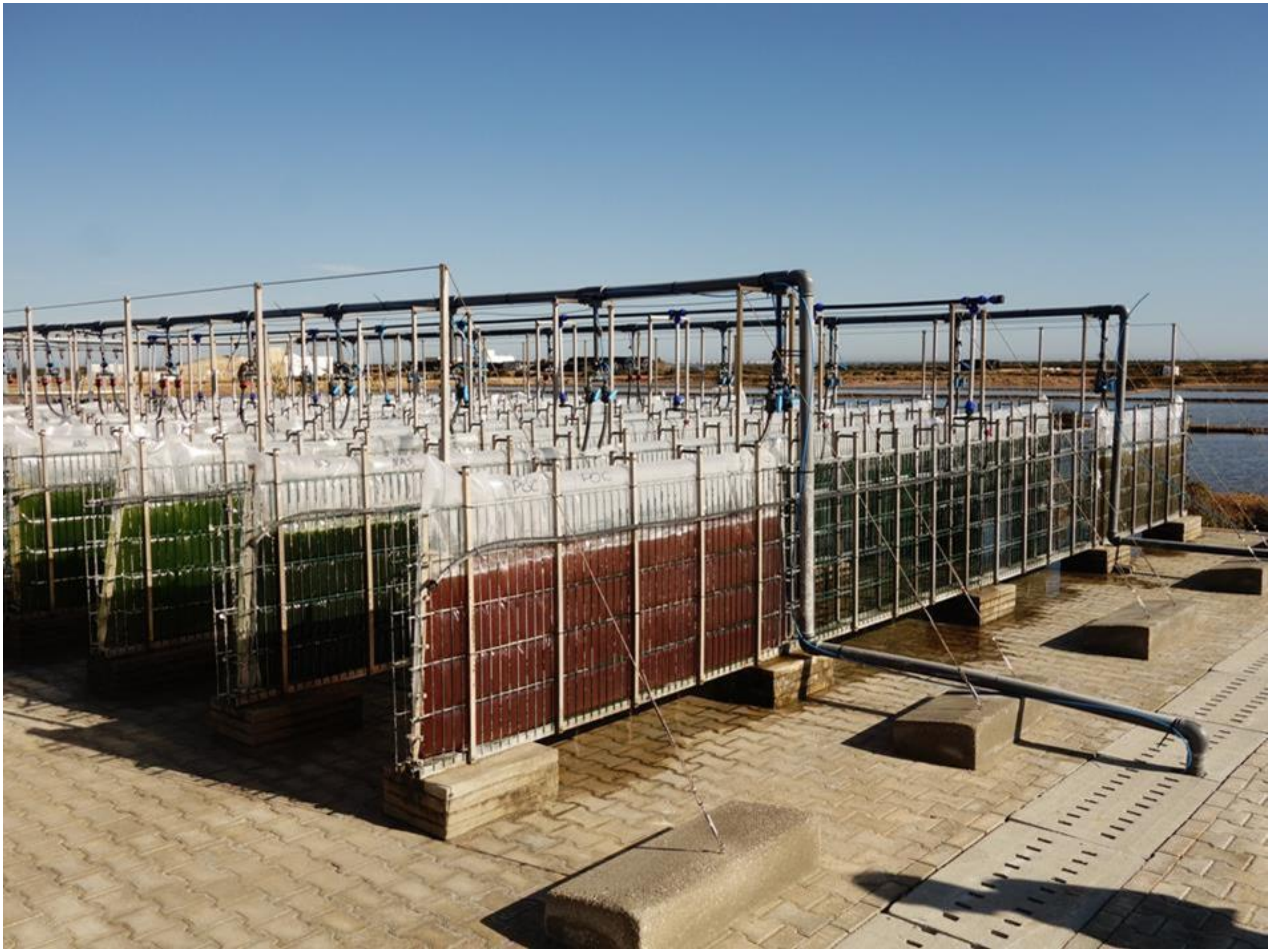
Algae Production: photo-bio-reactors



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Algae Production: raceways

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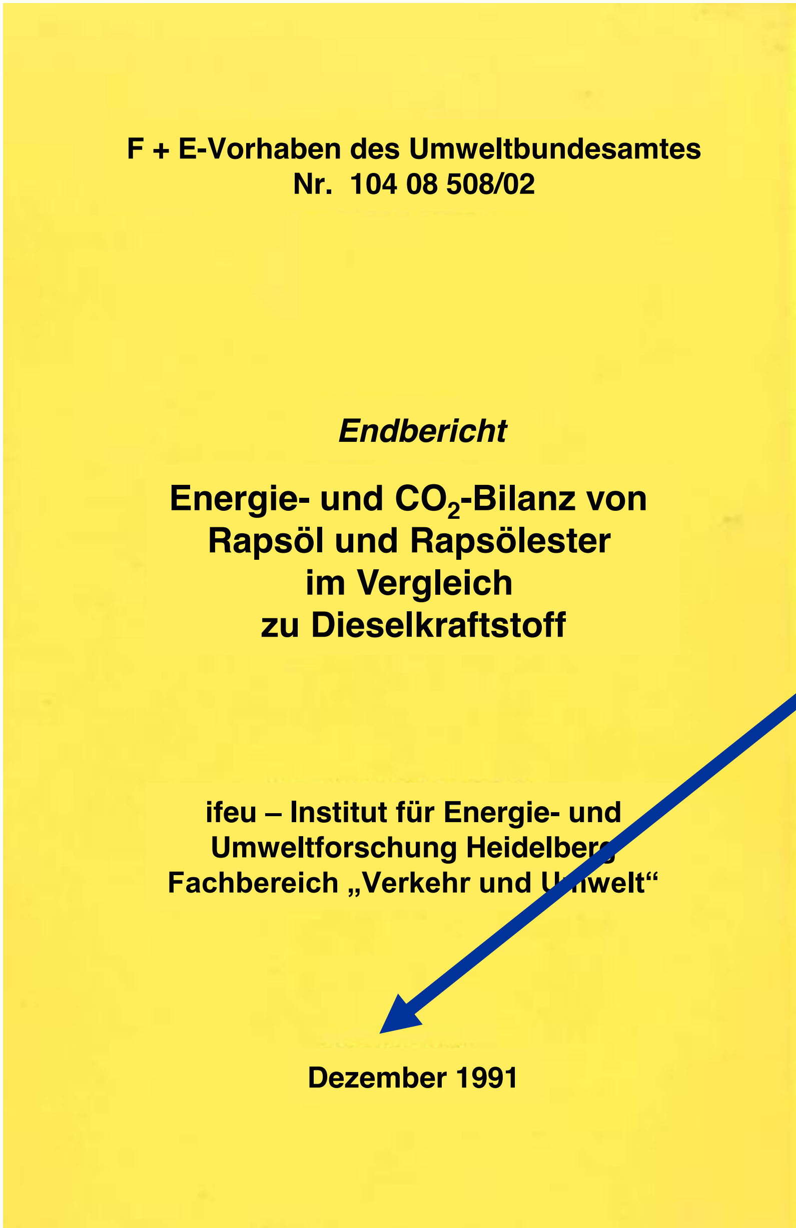
25 + years of experience



F + E-Vorhaben des Umweltbundesamtes
Nr. 104 08 508/02

Endbericht

Energie- und CO_2-Bilanz von Rapsöl und Rapsölester im Vergleich zu Dieselkraftstoff

ifeu – Institut für Energie- und Umweltforschung Heidelberg
Fachbereich „Verkehr und Umwelt"

Dezember 1991

First full life cycle balance on biodiesel in Europe

1991

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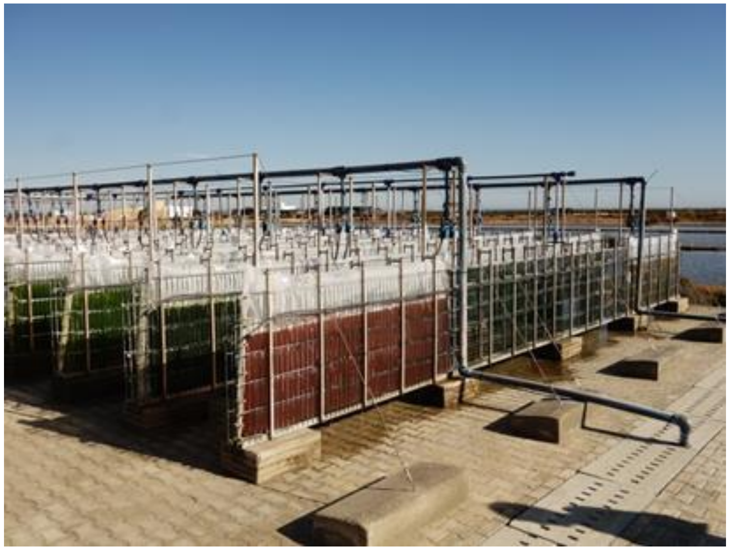
Algae Production: many options



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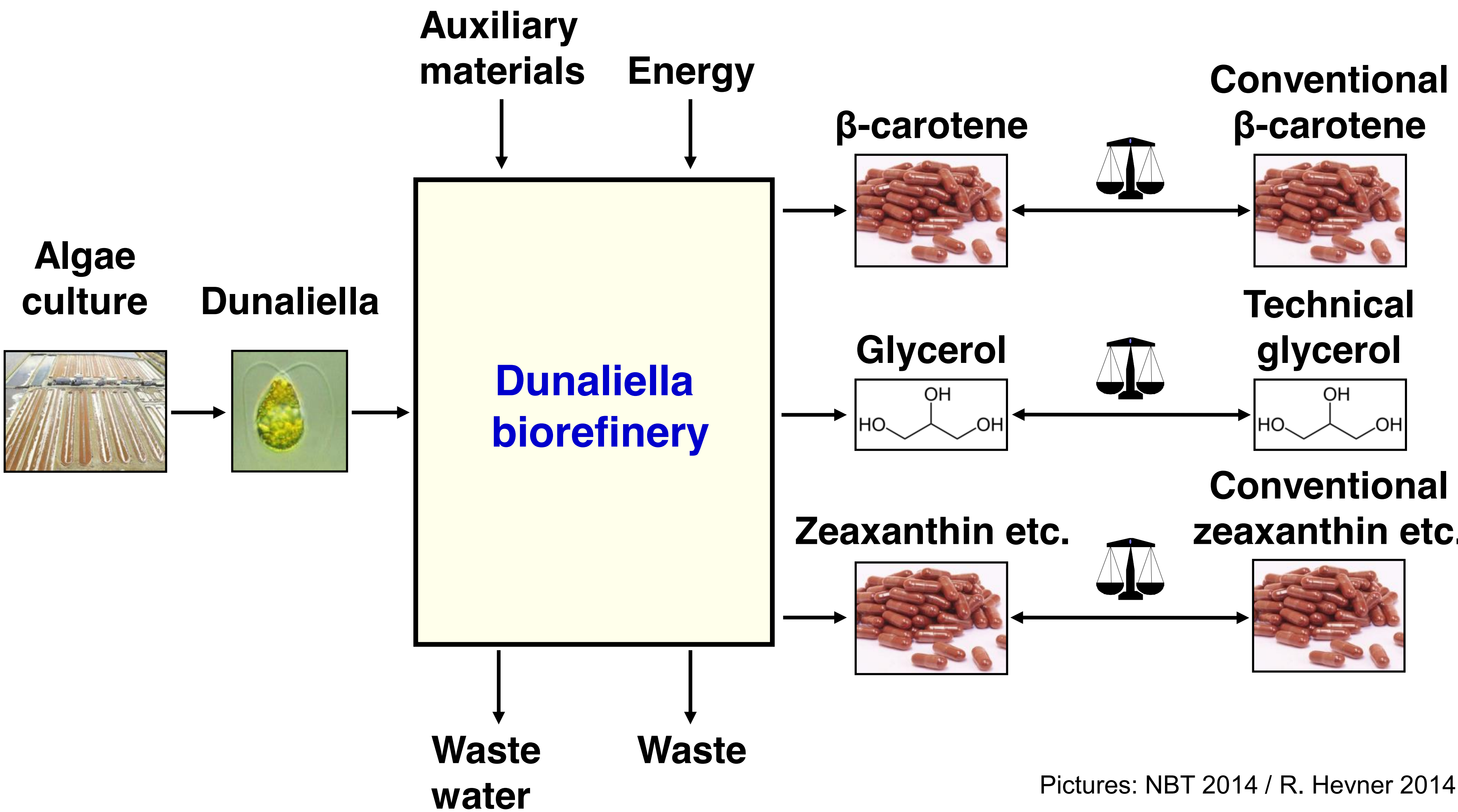
Algae based biorefinery of tomorrow



Pictures: NBT 2014 / R. Hevner 2014

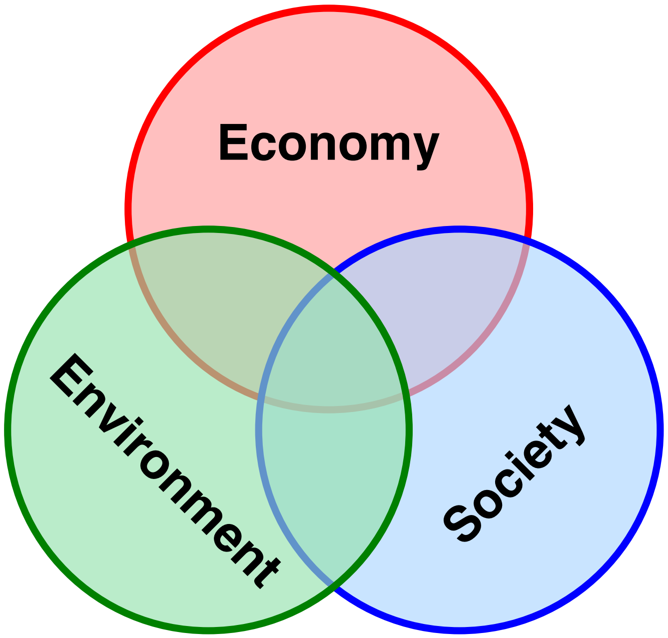
Sustainability

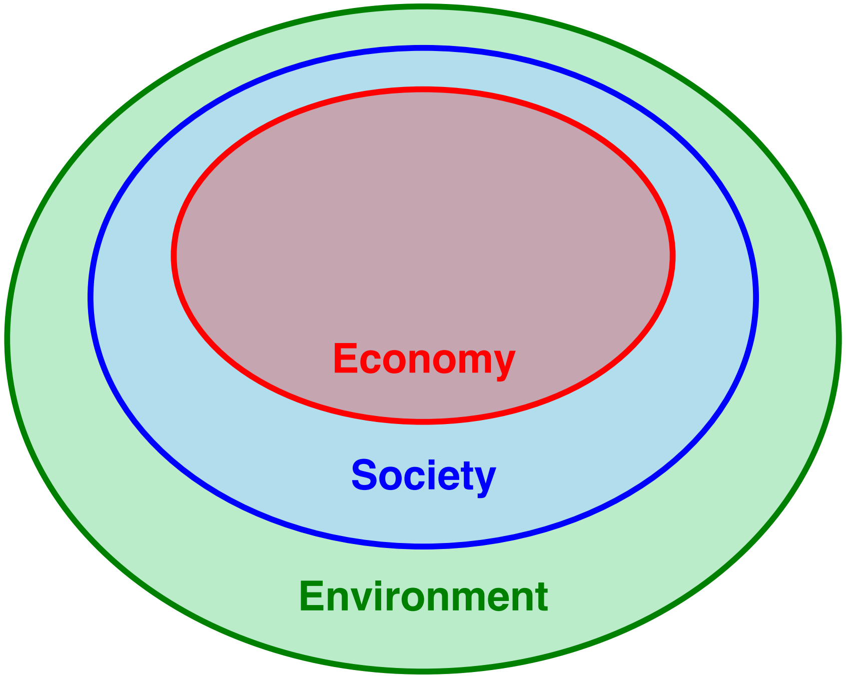
Definition

"Meeting the needs of the present generation without compromising the ability of future generations to meet their needs."

Brundtland Commission 1987

Sustainability

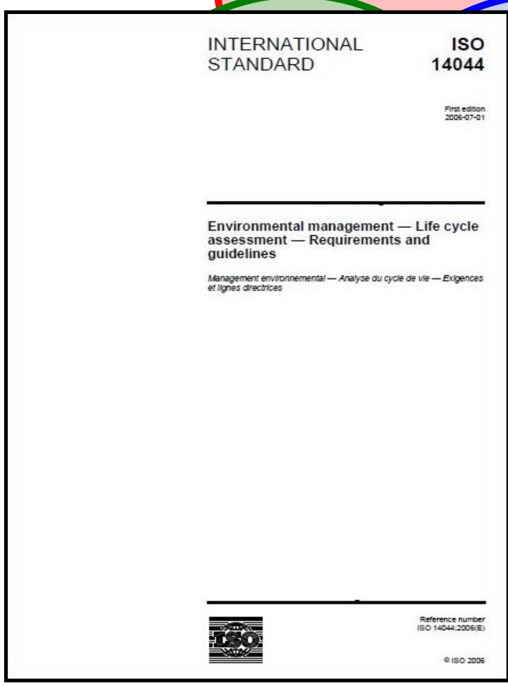




Sustainability

➔ **Not sufficient: e. g. technological, legal and political issues are not addressed sufficiently.**

Life Cycle Assessment (LCA)


INTERNATIONAL STANDARD

ISO 14044

First edition 2006-07-01

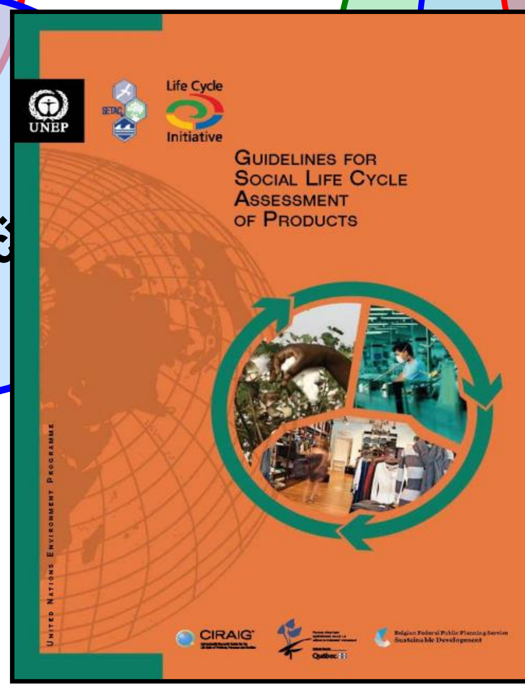
Environmental management — Life cycle assessment — Requirements and guidelines

Management environnemental — Analyse du cycle de vie — Exigences et lignes directrices

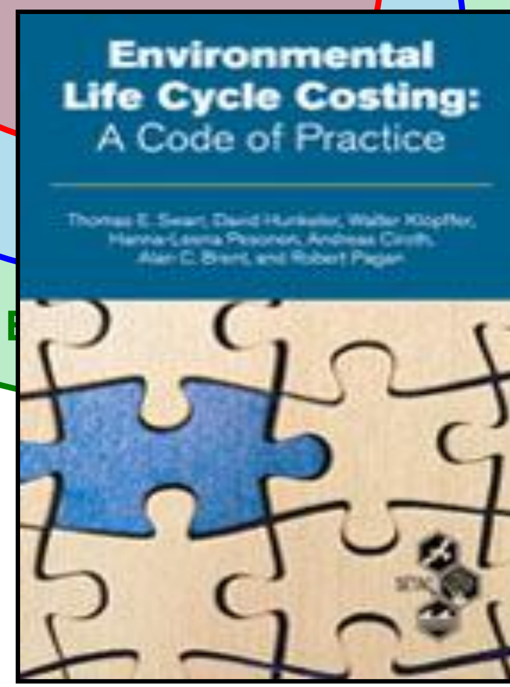
Reference number ISO 14044:2006(E)

© ISO 2006

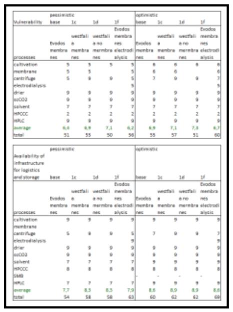
Social Life Cycle Assessment (sLCA)



Environmental Life Cycle Costing (eLCC)

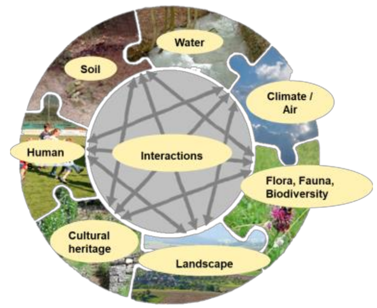


TA

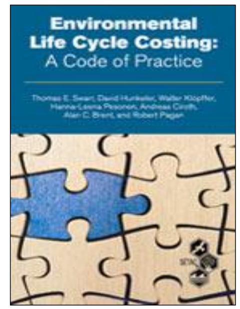


LCA

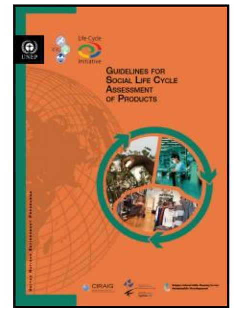
LC-EIA



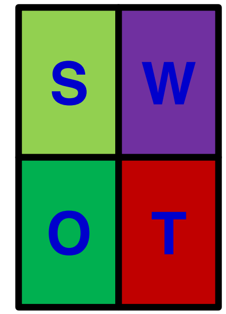
LCC

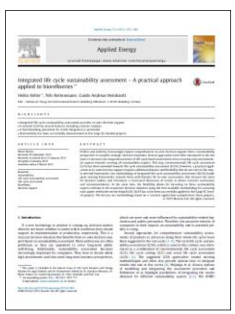


sLCA



SWOT

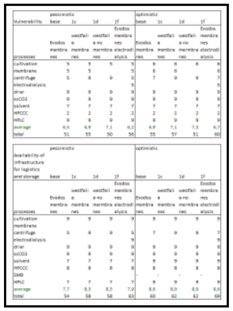


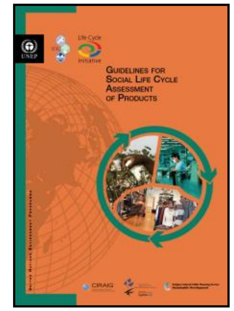


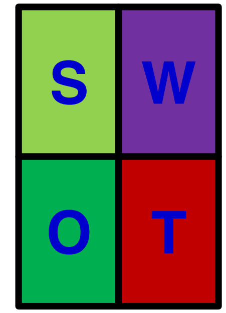
Integrated life cycle sustainability assessment

Technological assessment (TA)

TA-parameters under investigation



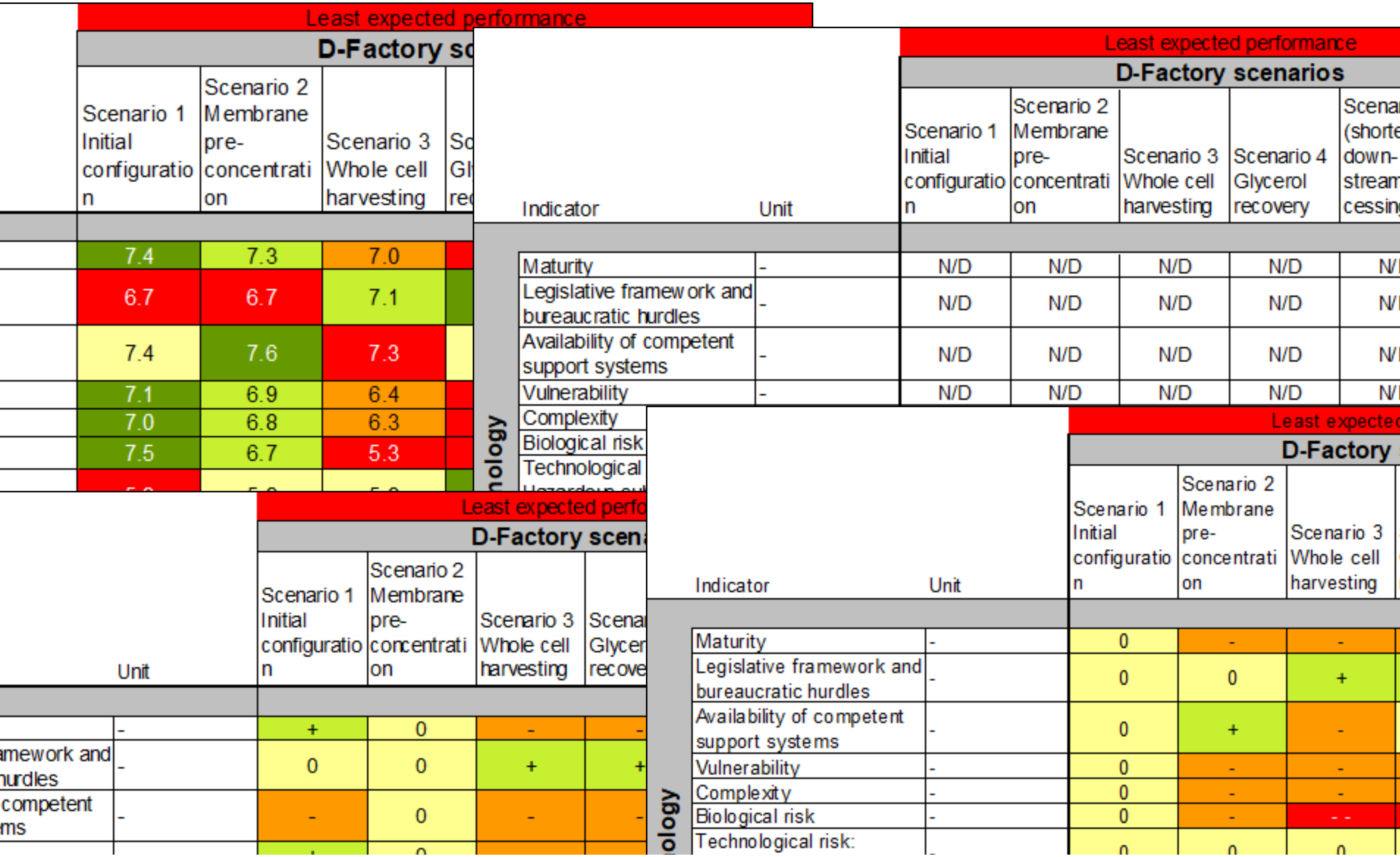




Vulnerability	pessimistic base	1c	1d	1f	optimistic base	1c	1d	1f
processes	Evodos membranes	westfalia membranes	westfalia no membranes	Evodos membranes electrodialysis	Evodos membranes	westfalia membranes	westfalia no membranes	Evodos membranes electrodialysis
cultivation	5	5	5	5	6	6	6	6
membrane	5	5		5	6	6		6
centrifuge	5	9	9	5	7	9	9	7
electrodialysis				5				5
drier	9	9	9	9	9	9	9	9
scCO2	9	9	9	9	9	9	9	9
solvent	7	7	7	7	7	7	7	7
HPCCC	2	2	2	2	2	2	2	2
HPLC	9	9	9	9	9	9	9	9
average	6,4	6,9	7,1	6,2	6,9	7,1	7,3	6,7
total	51	55	50	56	55	57	51	60

Availability of infrastructure for logistics and storage	pessimistic base	1c	1d	1f	optimistic base	1c	1d	1f
processes	Evodos membranes	westfalia membranes	westfalia no membranes	Evodos membranes electrodialysis	Evodos membranes	westfalia membranes	westfalia no membranes	Evodos membranes electrodialysis
cultivation	9	9	9	9	9	9	9	9
membrane								
centrifuge	5	9	9	5	7	9	9	7
electrodialysis				9				9
drier	9	9	9	9	9	9	9	9
scCO2	9	9	9	9	9	9	9	9
solvent	7	7	7	7	9	9	9	9
HPCCC	8	8	8	8	8	8	8	8
SMB					-	-	-	-
HPLC	7	7	7	7	9	9	9	9
average	7,7	8,3	8,5	7,9	8,6	8,9	8,9	8,6
total	54	58	58	63	60	62	62	69

TA results



Least expected performance

	D-Factory sc...			
	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Sc... Gl... rec...
	7.4	7.3	7.0	
	6.7	6.7	7.1	
	7.4	7.6	7.3	
	7.1	6.9	6.4	
	7.0	6.8	6.3	
	7.5	6.7	5.3	

Least expected performance

Indicator	Unit	D-Factory scenarios: Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenari (shorter down-stream cessing
Maturity	-	N/D	N/D	N/D	N/D	N/D
Legislative framework and bureaucratic hurdles	-	N/D	N/D	N/D	N/D	N/D
Availability of competent support systems	-	N/D	N/D	N/D	N/D	N/D
Vulnerability	-	N/D	N/D	N/D	N/D	N/D
Complexity						
Biological risk						
Technological						

Least expected perfo...

	Unit	D-Factory scen...: Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scena... Glycer... recove...
	-	+	0	-	-
...amework and ...urdles	-	0	0	+	+
... competent ...ms	-	-	0	-	-

Least expected

Indicator	Unit	D-Factory s...: Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting
Maturity	-	0	-	-
Legislative framework and bureaucratic hurdles	-	0	0	+
Availability of competent support systems	-	0	+	-
Vulnerability	-	0	-	-
Complexity	-	0	-	-
Biological risk	-	0	-	- -
Technological risk:	-	0	0	0

Technological assessment within the D-Factory project by P. Harvey (University of Greenwich, UK)
Technological assessment within the PUFAChain project by S. Reyer and M. Stehr (IOI Oleo, Germany)

TA results

Least expected performance

D-Factory sc

Scenario 1 Initial	Scenario 2 Membrane pre-	Scenario 3	Sc

Least expected performance

D-Factory scenarios

Scenario 1	Scenario 2 Membrane			Scenari (shorter

Exemplary results

→ Current technological improvements are ground-breaking.

→ Mature algae cultivation processes may therefore look quite different from current visions.

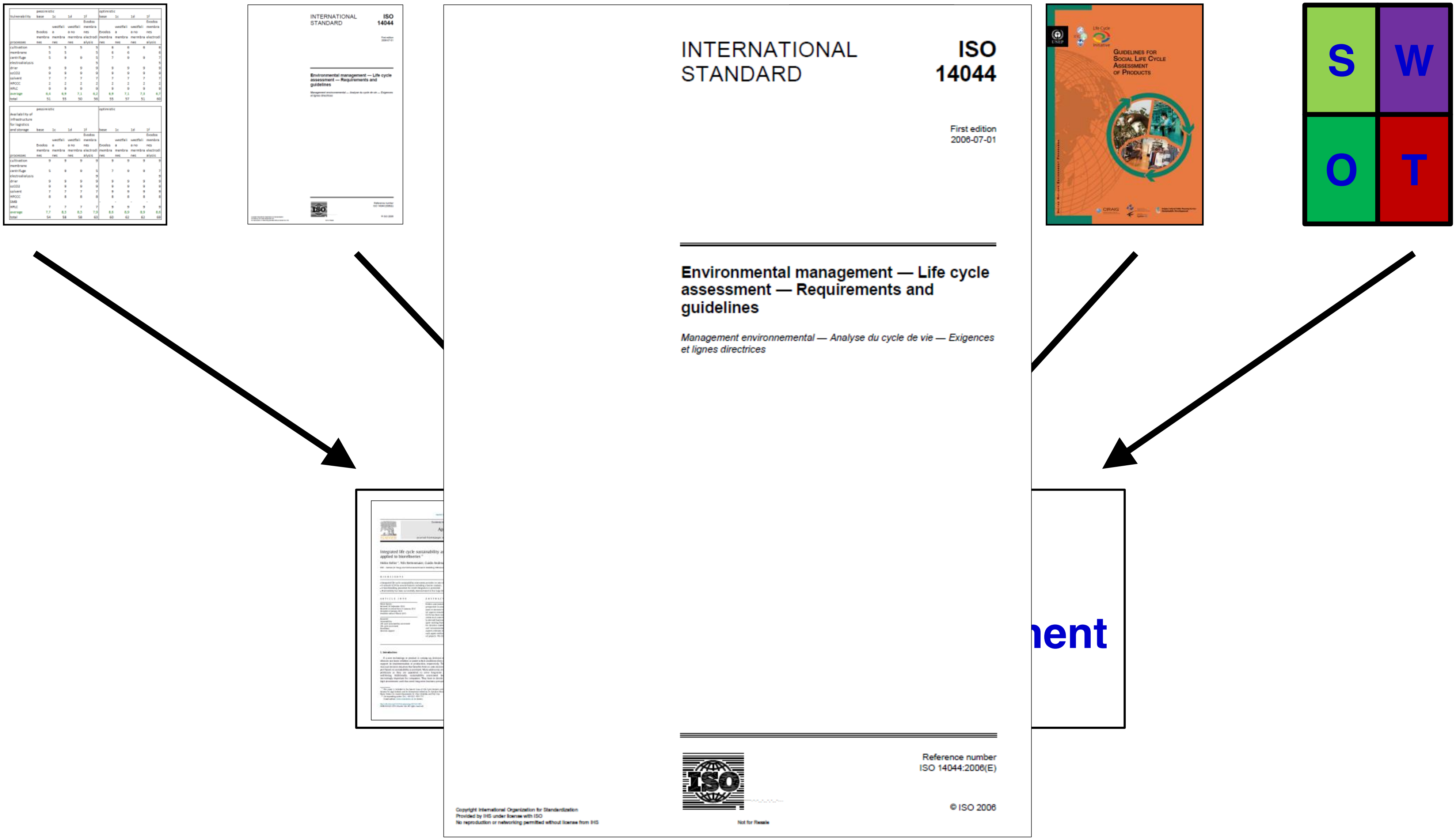
→ Industrial scale implementation still requires improvements.

→ …

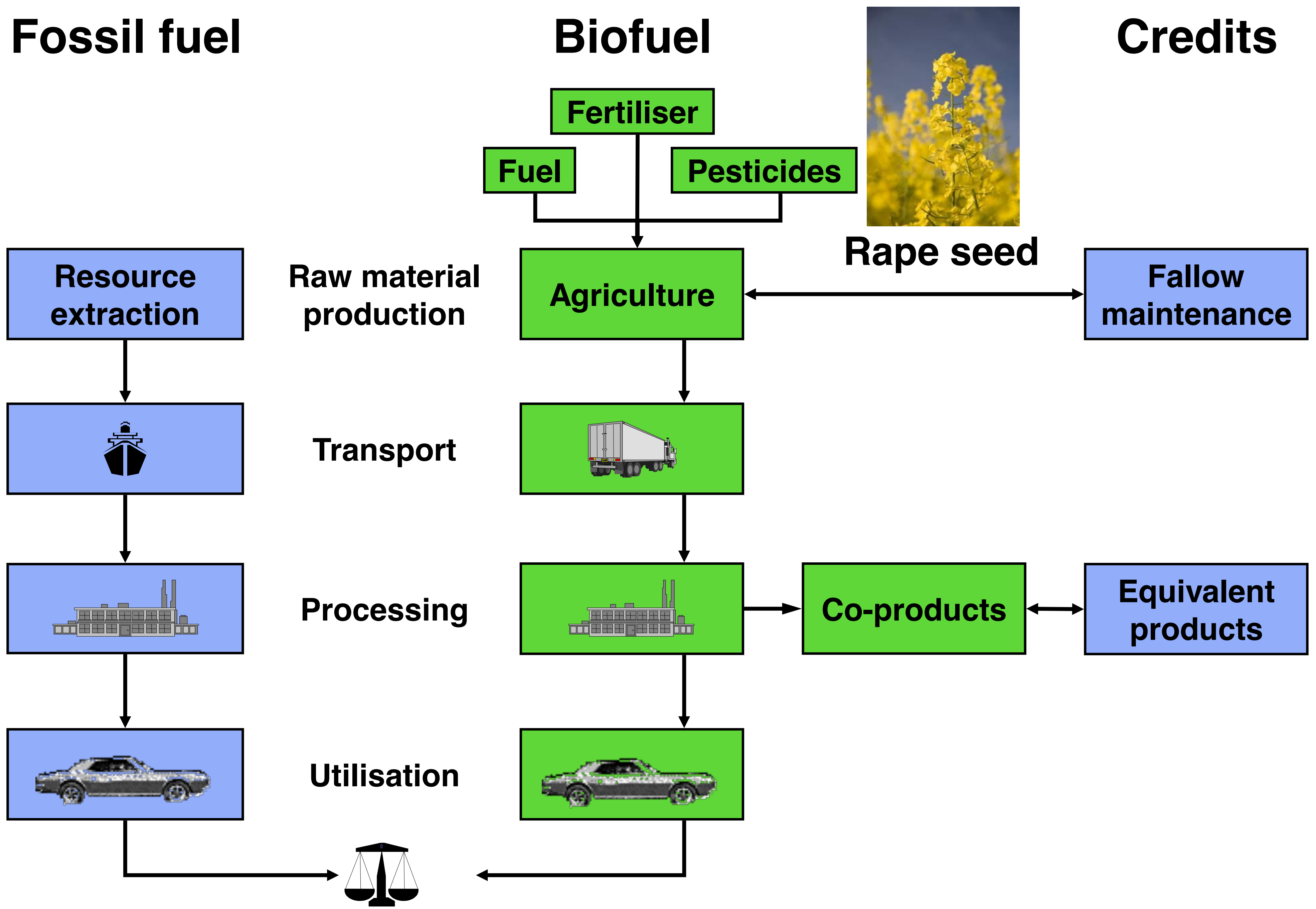
	-	+	0	-	-
	-	+	0	-	-
	-	+	0	- -	-

Technol	Technological risk: Hazardous substances	-	0	0	0
	Technological risk: Explosions and fires	-	0	0	0

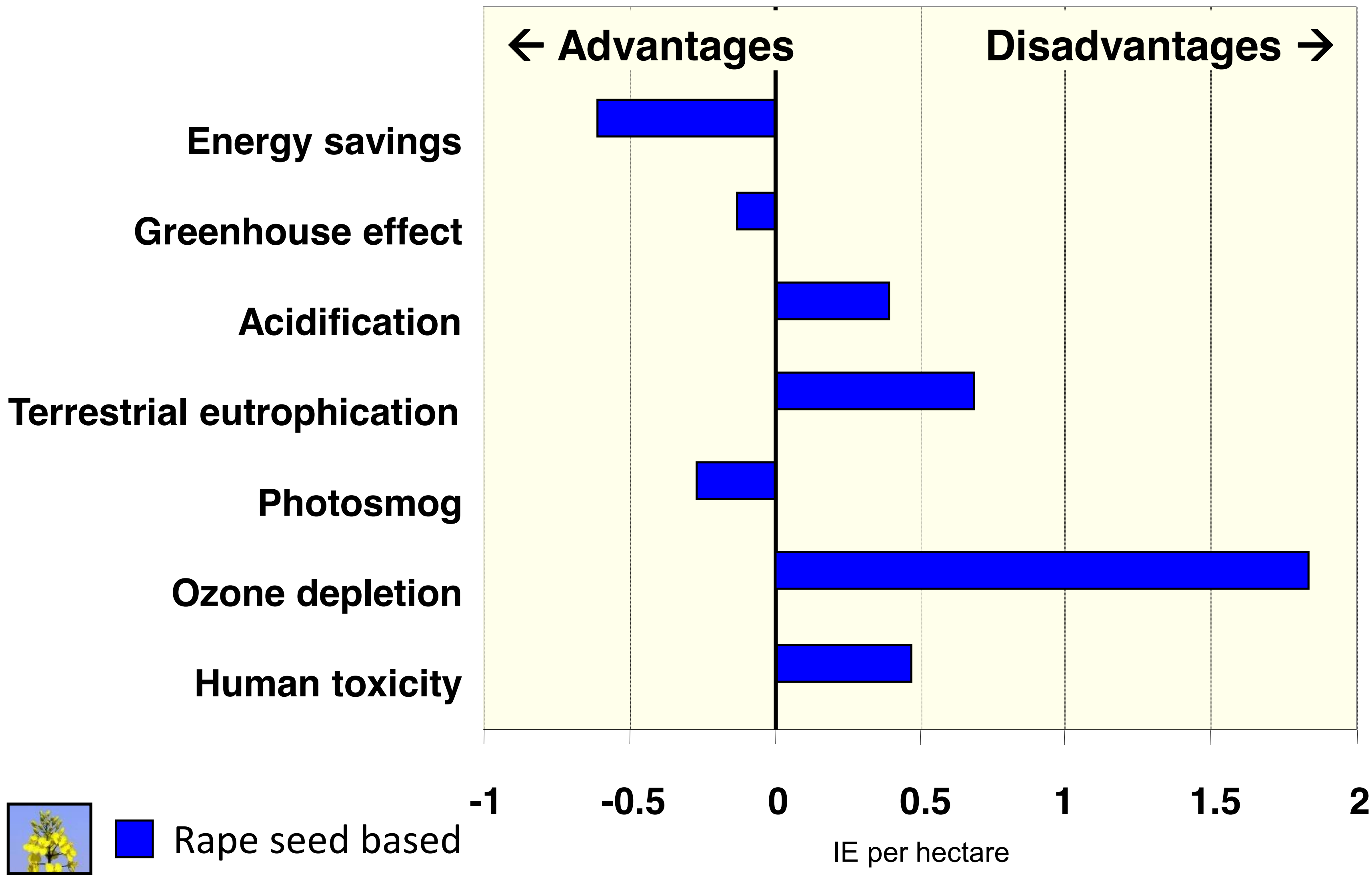
Life cycle assessment (LCA)



Life cycle comparison

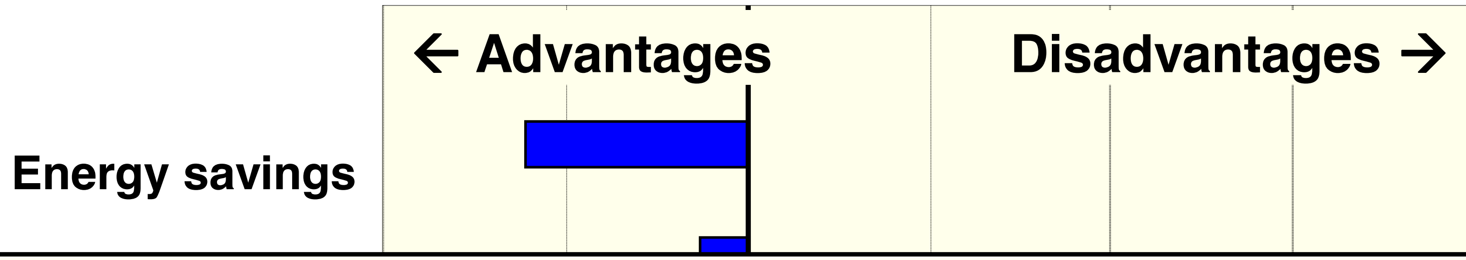


LCA results: biodiesel from rape seed



Source: IFEU 2017

LCA results: biodiesel from rape seed

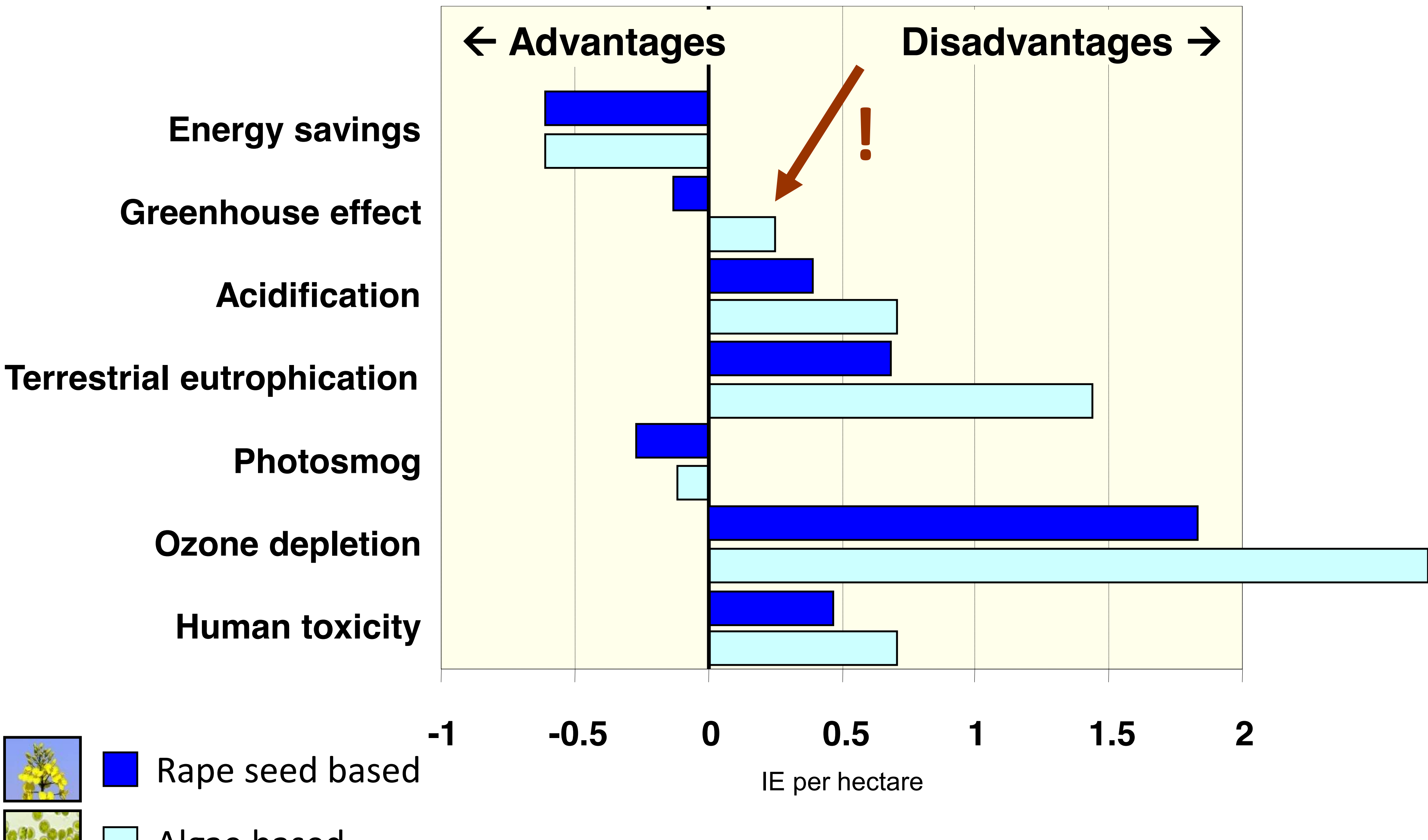


Algae based biofuels scenario I:

- Low production rate
- Low processing efficiency / high energy input
- Low amount of high value added products
- High amount of low value added products

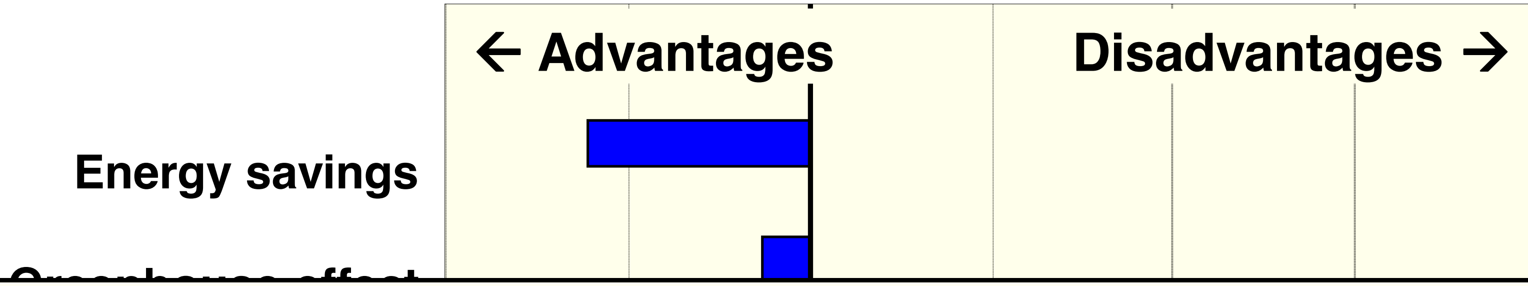
Source: IFEU 2017

LCA results: biodiesel



Source: IFEU 2017

LCA results: biodiesel from rape seed

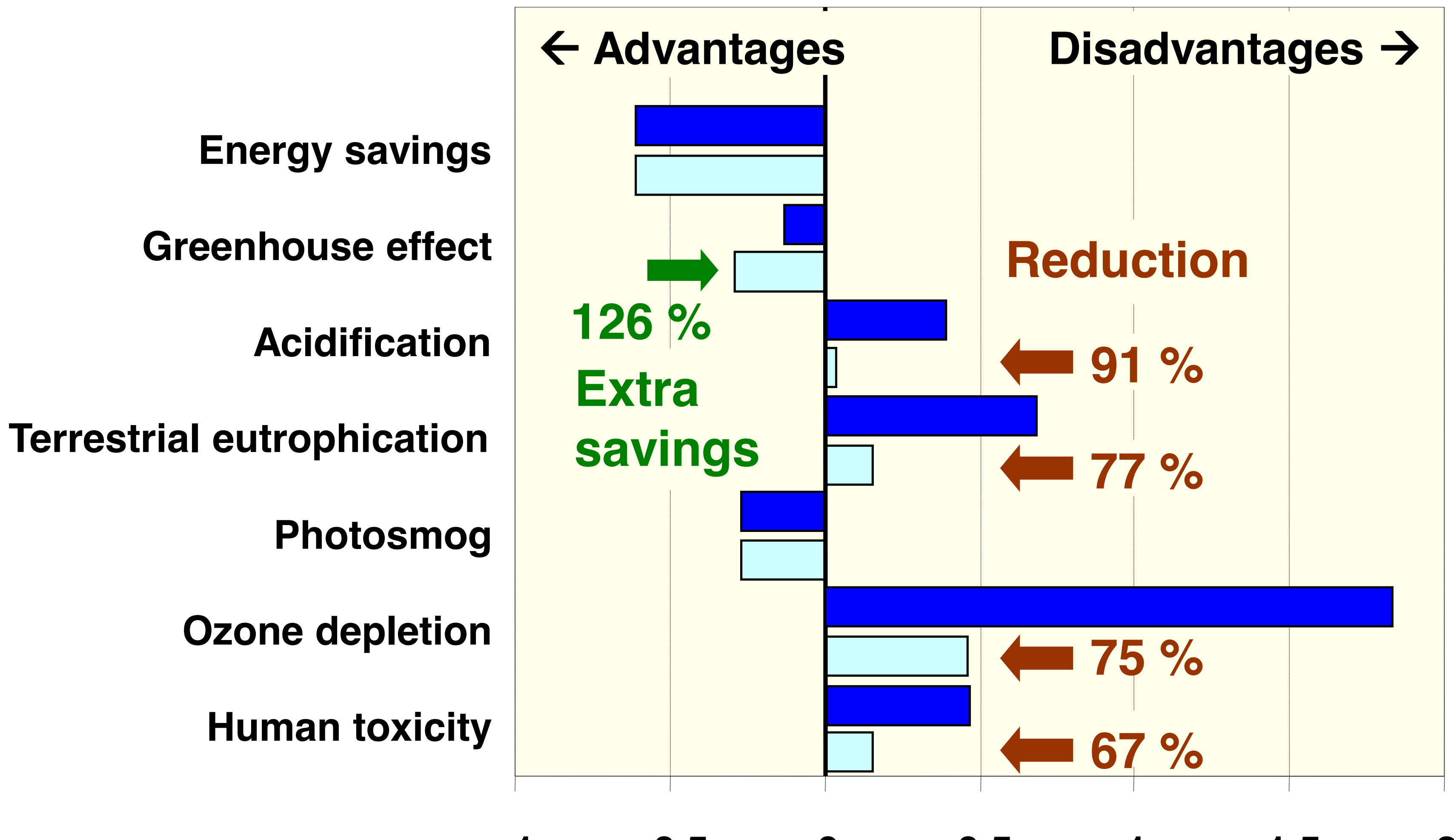


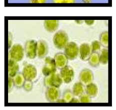
Algae based biofuels scenario II:

- Closed production units
- Typical processing efficiency
- Use of renewable energy for cultivation / processing
- Use of low input CO_2

Source: IFEU 2017

LCA results: biodiesel



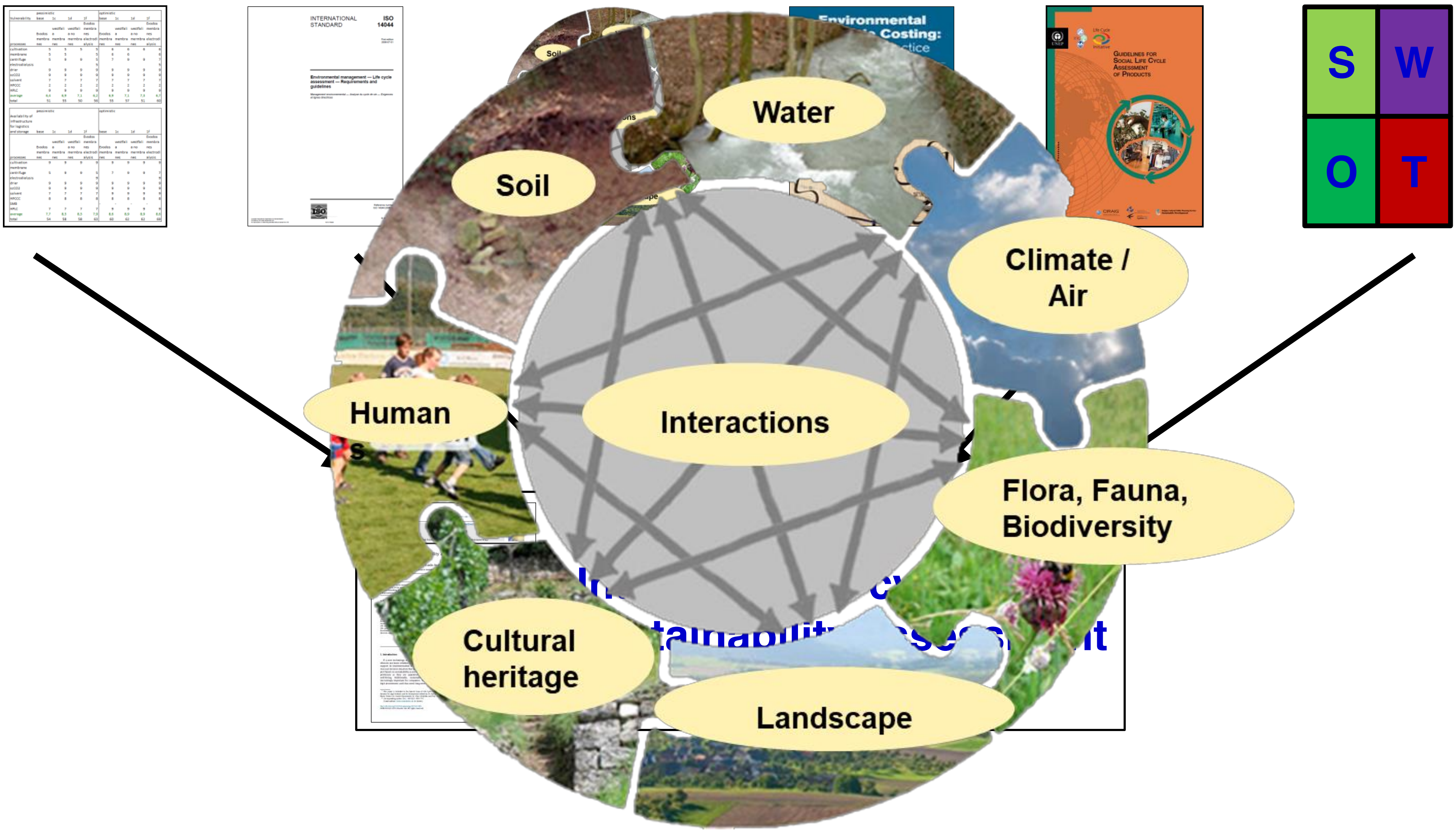
Source: IFEU 2017

LCA results

Exemplary results

- → Up to 90 % reduction in environmental burdens of algae based products realistic (environmentally optimised upscaling vs. “simple” upscaling).
- → Feed co-products can save up to 10 times the land that is needed for algae cultivation.
- → A better performance than competing products requires highly optimised algae cultivation and processing.
- → LCA is needed to identify and realise these potentials.
- → …

Life cycle-environmental impact assessment (LC-EIA)



Environmental assessment

Methodologies

- Life cycle assessment (LCA)
- Life cycle environmental impact assessment (LC-EIA)

LCA	LC-EIA
→ Global impacts	→ Site-specific impacts

LC-EIA results: examples

Life cycle-environmental impact assessment (LC-EIA)

Table 4-2 Technology-related impacts expected from the implementation of the PUFAChain system and its competing reference systems, respectively. Impacts are ranked in five comparative categories; “A” is assigned to the best options concerning the factor, “E” is assigned to unfavourable options concerning the factor

Algal/fish biomass (1-7) or biomass (8+9) provision	PUFAChain BF eco	PUFAChain BF grvl	PUFAChain GF eco	PUFAChain GF grvl	Ferm.	Cut-tings	By-catch	Soy-bean	Rape-seed
Impacts resulting from construction phase									
Construction works	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Impacts related to the facility itself (F) or resulting from operation phase (O)									
Soil sealing	A	C	C	D	n.a.	n.a.	n.a.	n.a.	n.a.
Soil erosion	A	n.a.	A	n.a.	D	n.a.	n.a.	D	D
Soil compaction	B	D	B	D	D	n.a.	n.a.	D	D
Loss of soil organic matter	n.a.	n.a.	n.a.	n.a.	E	n.a.	n.a.	C	C
Soil chemistry/fertiliser	n.a.	n.a.	n.a.	n.a.	E	n.a.	n.a.	D	D
Weed control/pesticides	n.a.	n.a.	n.a.	n.a.	E	n.a.	n.a.	E	E
Loss of habitat types	A	C	C/D	E	D	n.a.	n.a.	E	D
Loss of species	A	C	C/D	E	D	n.a.	n.a.	E	D

acts on the environment related to the provision of
tegories; "A" and "B" are assigned to the best optic
o unfavourable options concerning the factor

	Crude oil
	E
	D
s water)	C / D
dust, water, metal)	C / D
	C / D
equipment)	D
ipelines)	D
ichment	D
leakage)	E

Life cycle-envir

Table 6-3 Technology-related impacts expected from the implementation of the D-Factory reference systems, respectively. Impacts are ranked in five comparative categories; "A" is as concerning the factor, "E" is assigned to unfavourable options concerning the factor

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Mari-gold	Soy-bean
(Algal) biomass provision						
Impacts resulting from construction						
Construction works	C	C	C	C	C	C
Impacts related to the facility itself (F) and / or from operation (O)						
Soil sealing	E	D / E	D / E	D / E	n.a.	n.a.
Soil erosion	n.a.	n.a.	n.a.	n.a.	D	D
Soil compaction	E	D / E	D / E	D / E	D	D
Loss of soil organic matter	n.a.	n.a.	n.a.	n.a.	D	C
Soil chemistry / fertiliser	n.a.	n.a.	n.a.	n.a.	E	D
Weed control / pesticides	n.a.	n.a.	n.a.	n.a.	E	E
Loss of habitat types	E	D / E	D / E	D / E	D	E
Loss of species	E	D / E	D / E	D / E	C	E
Barrier for migratory animals	E	E	E	E	n.a.	n.a.

Soil sealing

	Marigold	Soybean
	Idle land	Idle land
	D	D
	D	D
	D	C
	E	D
	E	D
	E	D

Table 4-1 Comparison of crop-specific impacts compared to the reference system idle land. Impacts are ranked in five categories; "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor

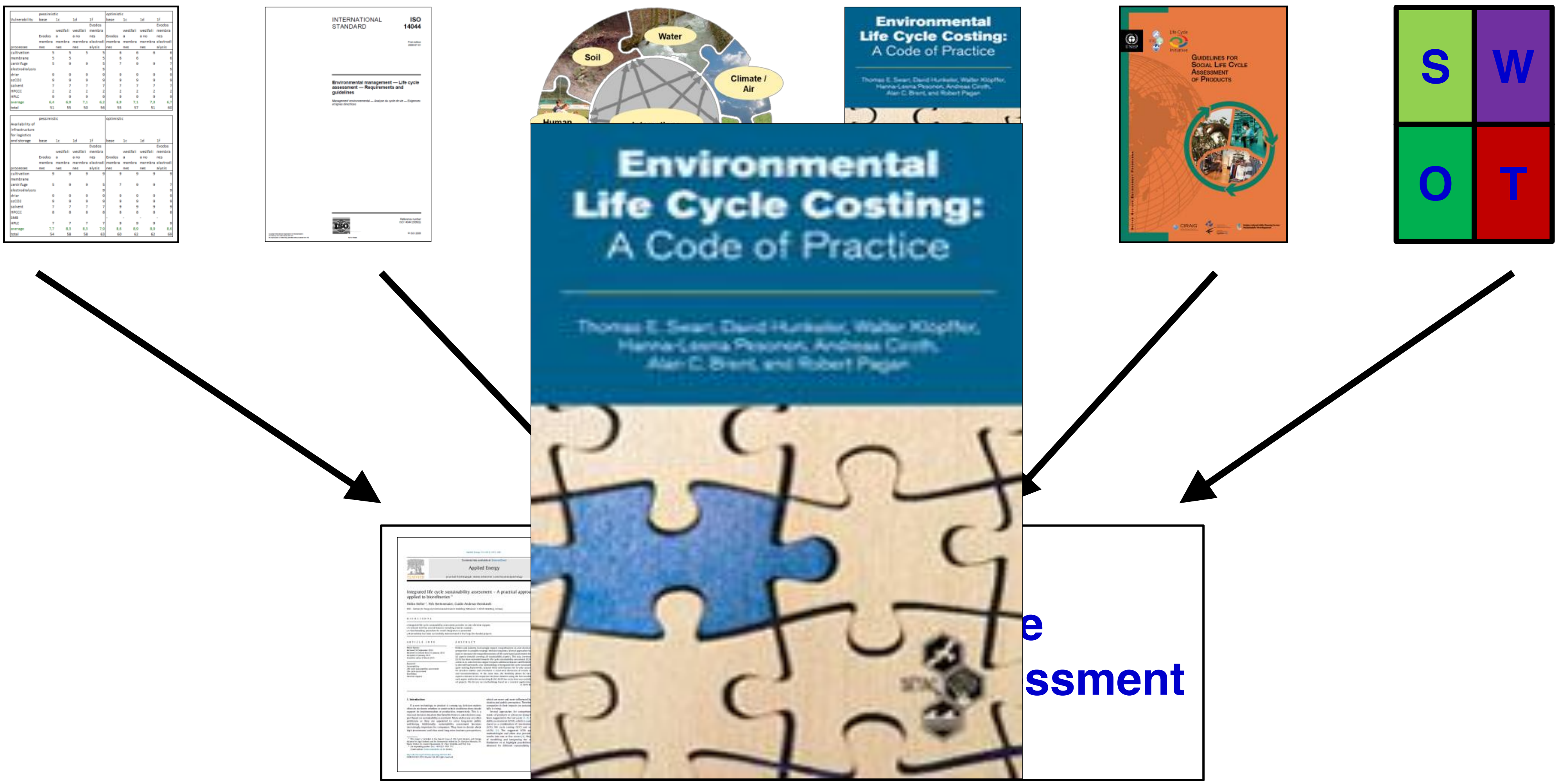
Feedstock	Sugar cane	Sugar beet	Maize	Avg. of crops
Reference system	Idle land	Idle land	Idle land	Idle land
Soil erosion	C	E	E	D
Soil compaction	D	E	D	D
Loss of soil organic matter	E	E	E	E
Soil chemistry/fertiliser	D	E	E	E
Eutrophication	D	D	D	D
Nutrient leaching	D	D	D	D
Water demand	D	E	D	D

LC-EIA results

Exemplary results

- ➔ Arable land should not be converted into algae cultivation sites.
- ➔ Closed algae cultivation systems can be upgraded by meadows underneath and hedges around.
- ➔ Freshwater and saltwater management requires adaptation to local conditions.
- ➔ Also saltwater algae cultivation and processing can require substantial amounts of freshwater.
- ➔ …

Life cycle costing (LCC)



LCC results

Table 4-3 LCC outcome for dedicated EPA production in Southern and Central Europe

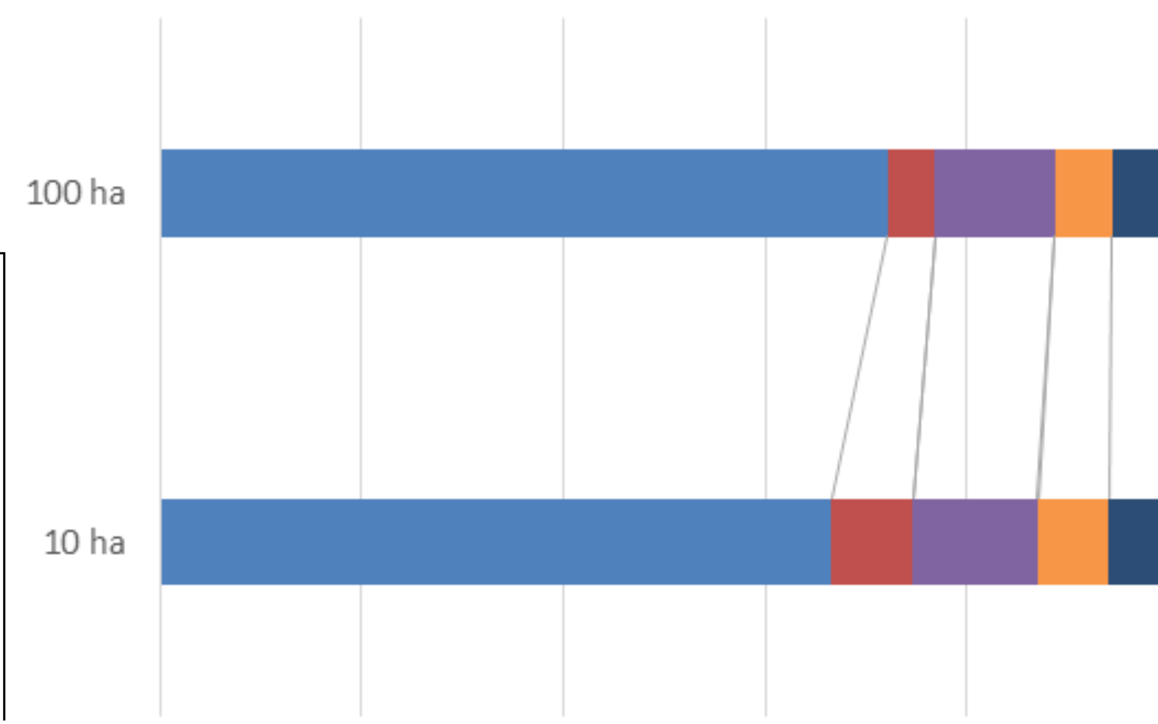
	Values for dedicated EPA production	
Scenario/cost price PUFA (€/kg)	**Least expected (10 ha)**	**Optimistic (100 ha)**
Southern Europe	1,156	932
Central Europe	2,344	1,915
Northern Europe	-	4,017

Table 4-1

Scenario/cost price PUFA (€/kg)
Southern Europe
Central Europe

d PUFA production (*Thalassiosira weissflogii*) in
nder least expected and optimistic conditions (on
ly)

Values for initial combined PUFA production	
Least expected (10 ha)	**Optimistic (100 ha)**
1,359	468
2,058	753



Socio-economic assessment within the PUFAChain project by
M. van der Voort, J. Spruijt, J. Potters, P. de Wolf and H. Elissen (Wageningen Research, the Netherlands)
Economic assessment within the D-Factory project by P. Goacher and R. Mitchell (Hafren Investments, UK)

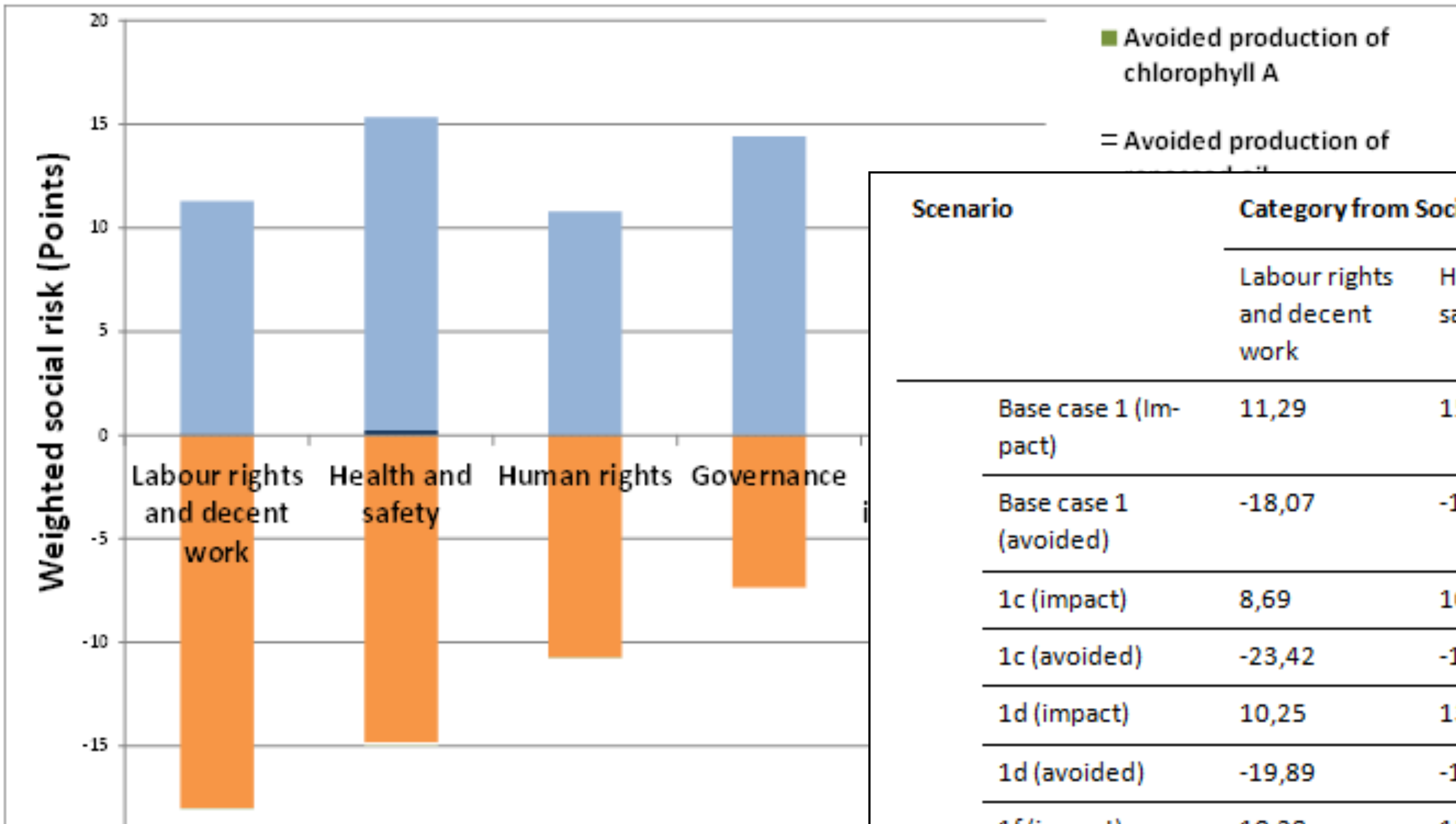
LCC results

Exemplary results

- → Profitability for algae based products can be reached but mostly only in highly optimised systems.
- → Costs can be significantly lower in rural communities.
- → Using own solar power instead of grid power for algae cultivation and processing can reduce life cycle costs.
- → Economic assessment e.g. by LCC is necessary to identify cost drivers and optimise performance.
- → …

Social life cycle assessment (sLCA)

sLCA results



Scenario		Category from Social Hotspot Index (Risk of negative impact/			
		Labour rights and decent work	Health and safety	Human rights	Governa
	Base case 1 (Im-pact)	11,29	15,34	10,78	14,41
	Base case 1 (avoided)	-18,07	-15,01	-10,77	-7,43
Optimistic performance	1c (impact)	8,69	10,09	9	11,24
	1c (avoided)	-23,42	-19,36	-13,95	-9,61
	1d (impact)	10,25	13,88	9,54	12,67
	1d (avoided)	-19,89	-16,44	-11,85	-8,16
	1f (impact)	10,38	15,9	9,31	12,64
	1f (avoided)	-18,38	-15,24	-10,99	-7,67
	1g (impact)	5,58	13,1	2,62	5,04
	1g (avoided)	-22,41	-13,13	-17,1	-7,89
	1h (impact)	7,02	11,05	5,68	8,58
	1h (avoided)	-24,51	-17,05	-17,49	-10,78
affing	Double (impact)	11,3	15,49	10,74	14,4
	Double (avoided)	-18	-14,94	-10,72	-7,4
	Half (impact)	11,28	15,26	10,8	14,42
	Half (avoided)	-18,11	-15,04	-10,79	-7,45

Table 5-2: Summary of the results obtained for all the scenarios analysed

Scenario		Category from Social Hotspot Index (Risk of nega		
		Labour rights and decent work	Health and safety	Human rights
	Base case 1 (Im-pact)	12,31	23,59	8,82
	Base case 1 (avoided)	-11,7	-9,72	-6,97

Social assessment within the D-Factory project by D. Penaloza and S. Stahl (Research institutes of Sweden, Sweden)

sLCA results

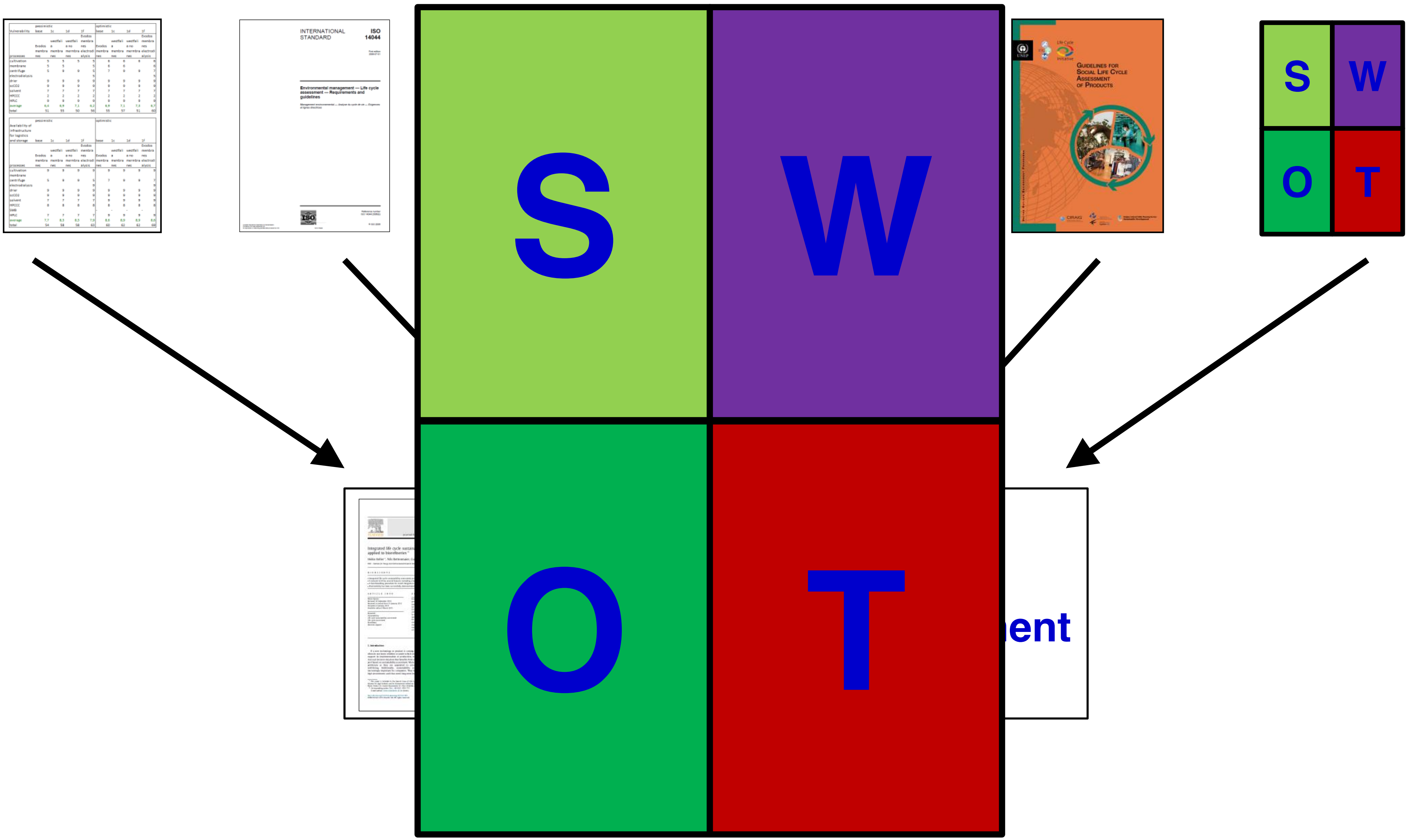
Exemplary results

- ➔ **Social risks are highly dependent on the country.**
- ➔ **At least for algae-based systems, no pronounced differences are found within the EU.**
- ➔ **Risks need to be monitored.**
- ➔ **sLCA is essential to identify social related risks in the supply chain.**
- ➔ **…**

1g (avoided)	-13,31	-7,74
1h (impact)	9,81	19,79
1h (avoided)	-16,23	-11,23

Scenario	Category from Social Hotspot Index (Risk of negative impact/ year)				
Half (avoided)	-18,11	-15,04	-10,79	-7,45	-14,38
Israel (impact)	10,37	22,88	17,97	9,51	5,21
Israel (avoided)	-12,54	-10,41	-7,47	-5,15	-9,95

Strengths, weaknesses, opportunities, and threats (SWOT)



SWOT results

STRENGHTS
Composition DHA/EPA
Production process
Production in northern countries
Pure product
High value product
Mixotrophic system
By-products of algae production

WEAKNESSES
Energy consumption in the production of algae

PU

OPPORTUNITIES
Declining fish stocks
Growing market
Positive image of algae

(SWOT)

SWOT Analysis on algae bioprocessing system

	Helpful to achieving the objective	Harmfu[l] to achieving the
Internal origin (attributes of the system)	*Strengths* • Unique combination of centri-fuge+ScCO2+HPCCC + membrane extraction • Potential high value product • Waste stream minimization	*Weaknesses* • Clinical trials put into pl • Most promising algae s current/future market v ternalities not decided y • Some of the flagship pr quantitatively assessed • Some techniques are st
…iron-	*Opportunities* • Extraction processes of the D-Factory an-	*Threats* • Market demand side (n maceutical) is n e harder than th legislation ity and contrac dstock

SWOT Analysis of algae biomass cultivation

	Helpful to achieving the objective	Harmful to achieving the objective
rnal origin (…tes of the sys-tem)	*Strengths* • Salt & performant/resistant algal strain control and reduce contamination • Raceway ponds with CO2 input are easier to build	*Weaknesses* • Land use associated costs can be high • Brine and power plant/industries are not available everywhere

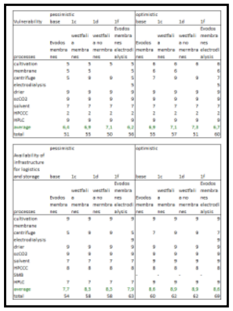
SWOT analysis within the PUFACain project by
M. van der Voort, J. Spruijt, J. Potters, P. de Wolf and H. Elissen (Wageningen Research, the Netherlands)
SWOT analysis within the D-Factory project by S. Stahl (Research institutes of Sweden, Sweden)

SWOT results

Exemplary results

- ➔ Additional valuable inputs from different stakeholders via SWOT analyses can significantly supplement the prior listed findings.
- ➔ Stakeholders' views are important in particular if they contradict results of detailed analyses.
  - For checking analyses
  - For correcting wrong impressions
- ➔ Need for SWOT analyses to supplement the analytical assessments.
- ➔ …

Integrated life cycle sustainability assessment (ILCSA)



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Integrated life cycle sustainability assessment – A practical approach applied to biorefineries ☆

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HIGHLIGHTS

- Integrated life cycle sustainability assessment provides ex-ante decision support.
- It extends LCSA by several features including a barrier analysis.
- A benchmarking procedure for result integration is presented.
- Practicability has been successfully demonstrated in five large EC-funded projects.

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ABSTRACT

Politics and industry increasingly request comprehensive ex-ante decision support from a sustainability perspective in complex strategic decision situations. Several approaches have been introduced in the last years to increase the comprehensiveness of life cycle based assessments from covering only environmental aspects towards covering all sustainability aspects. This way, (environmental) life cycle assessment (LCA) has been extended towards life cycle sustainability assessment (LCSA). However, a practical application in ex-ante decision support requires additional features and flexibility that do not exist in the newly devised frameworks. Our methodology of integrated life cycle sustainability assessment (ILCSA) builds upon existing frameworks, extends them with features for ex-ante assessments that increase the value for decision makers and introduces a structured discussion of results to derive concrete conclusions and recommendations. At the same time, the flexibility allows for focusing on those sustainability aspects relevant in the respective decision situation using the best available methodology for assessing each aspect within the overarching ILCSA. ILCSA has so far been successfully applied in five large EC-funded projects. We discuss our methodology based on a concrete application example from these projects.
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1. Introduction

If a new technology or product is coming up, decision makers often do not know whether or under which conditions they should support its implementation or production, respectively. This is a classical decision situation that benefits from ex-ante decision support based on sustainability assessment. Main addressees are often politicians as they are appointed to serve long-term public well-being. Additionally, sustainability assessment becomes increasingly important for companies. They have to decide about high investments and thus need long-term business perspectives, which are more and more influenced by sustainability-related legislation and public perception. Therefore, the proactive interest of companies in their impacts on sustainability and in potential pitfalls is rising.

Several approaches for comprehensive sustainability assessments of products or processes along their whole life cycles have been suggested in the last years [1–3]. The term life cycle sustainability assessment (LCSA), which is used in this context, was introduced as a combination of (environmental) life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (sLCA) [1]. The suggested LCSA approaches extend existing methodologies and often also provide options how to integrate results into one or few scores [4]. Heijungs et al. discuss options of modelling and integrating the assessment procedure and Finkbeiner et al. highlight possibilities of integrating the results obtained for different sustainability aspects [2,3]. The UNEP/

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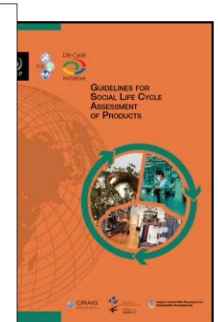
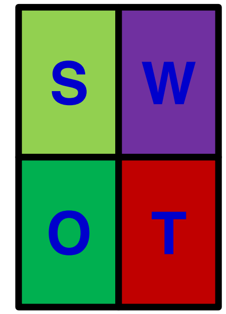
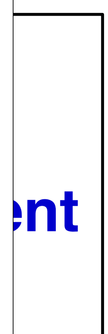






ILCSA results

Integrated life cycle sustainability assessment (ILCSA)

Table 5-4: Overview of results for life cycle comparisons of D-Factory scenarios to its alternatives. N/D: no data, N/A: not applicable.

			Least expected performance						Optimistic performance					
			D-Factory scenarios						D-Factory scenarios					
	Indicator	Unit	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)
Technology	Maturity	-	7.4	7.3	7.0	6.9	N/D	N/D	7.4	7.3	7.0	6.9	N/D	N/D
	Legislative framework and bureaucratic hurdles	-	6.7	6.7	7.1	7.4	N/D	N/D	6.7	6.7	7.1	7.4	N/D	N/D
	Availability of competent support systems	-	7.4	7.6	7.3	7.4	N/D	N/D	7.4	7.6	7.3	7.4	N/D	N/D
	Vulnerability	-	7.1	6.9	6.4	6.2	N/D	N/D	7.1	6.9	6.4	6.2	N/D	N/D
	Complexity	-	7.0	6.8	6.3	6.0	N/D	N/D	7.0	6.8	6.3	6.0	N/D	N/D
	Biological risk	-	7.5	6.7	5.3	5.3	N/D	N/D	7.5	6.7	5.3	5.3	N/D	N/D
	Technological risk: Hazardous substances	-	5.8	5.8	5.8	5.9	N/D	N/D	5.8	5.8	5.8	5.9	N/D	N/D
	Technological risk: Explosions and fires	-	7.4	7.4	7.4	7.5	N/D	N/D	7.4	7.4	7.4	7.5	N/D	N/D
Environment	Global warming	t CO2 eq. / kg 9-cis β-c.	26	22	27	26	5	1	14	12	15	15	2	0.2
	Energy resources	GJ / kg 9-cis β-c.	457	397	482	473	78	21	254	222	278	272	37	4
	Acidification	kg SO2 eq. / kg 9-cis β-c.	112	101	123	122	11	4	64	59	72	72	4	1
	Eutrophication	kg PO4 eq. / kg 9-cis β-c.	5.2	4.5	5.4	5.3	0.6	0.3	2.9	2.5	3.1	3.0	0.2	0.1
	Photosmog	kg ethene eq. / kg 9-cis β-c.	13	12	15	14	7	0.3	8	7	9	9	5	0.1
	Ozone depletion	g CFC-11 eq. / kg 9-cis β-c.	14	13	14	14	-0.4	1	7	6	7	7	-2	1
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg 9-cis β-c.	110	89	106	105	13	5	63	50	61	60	4	1
	Water	-	- -	-	-	-	-	-	-	0	0	0	0	0
	Soil	-	-	0	0	0	0	-	0	+	+	+	+	+
	Fauna	-	-	0	0	0	0	-	0	+	+	+	+	+
	Flora	-	-	0	0	0	0	-	0	+	+	+	+	+
	Landscape	-	0	0	0	0	0	0	+	+	+	+	+	+
Economy	Operating Expenditure	Million €/year	19	12	17	17	12	4	35	22	32	32	21	4
	Total Revenue	Million €/year	16	16	19	19	11	0	46	46	55	55	28	0
	Gross Margin	%	-23%	22%	10%	11%	-4%	N/A	24%	52%	42%	43%	28%	N/A
	Breakeven Revenue	Million €/year	-1.6	1.8	3.7	3.5	-9.1	0.0	1.6	0.7	0.9	0.9	1.4	0.0
	Capital Expenditure	Million €	51	50	50	50	1	1	51	50	50	50	1	1
	Economic Internal Rate of Return (10 years)	%	N/A	-2%	-17%	-15%	N/A	N/A	27%	83%	81%	83%	N/A	N/A
	Net Present Value (10 years, 5% discount)	Million €	-112	-15	-34	-33	-14	-64	64	186	183	185	75	-63
Society	Labor rights and decent work	Risk of negative impact/ t 9-cis β-carotene	-1.8	-3.0	0.4	-0.2	-3.8	-1.6	-2.4	-3.0	-1.4	-1.7	-3.4	-3.0
	Health and safety		9.6	9.1	10.2	10.5	5.0	5.9	-0.6	-1.0	0.1	0.1	-1.2	0.0
	Human rights		0.1	-1.1	1.4	0.5	-3.1	-2.5	-0.6	-1.0	0.0	-0.3	-2.3	-2.6
	Governance		6.4	5.2	6.7	5.6	2.0	1.2	1.1	0.6	1.4	1.0	-0.4	-0.5
	Community infrastructure		-4.8	-5.8	-2.7	-3.2	-5.1	-2.7	-2.5	-2.9	-1.7	-1.9	-3.2	-2.9

ILCSA results

Table 5-5: Comparison of all other scenarios to the benchmark scenario 1 (initial configuration) under optimistic conditions. N/D: no data, N/A: not applicable.

Table 5-6: Comparison of all other scenarios to the benchmark scenario 2 (membrane pre-concentration), under optimistic conditions. N/D: no data, N/A: not applicable.

	Indicator	Unit	Least expected performance – D-Factory scenarios: Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream processing)	Scenario 6 (no carotenoid separation)	Optimistic performance – D-Factory scenarios: Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream processing)	Scenario 6 (no carotenoid separation)
Technology	Maturity	-	+	0	-	-	N/D	N/D	+	BENCHMARK	-	-	N/D	N/D
	Legislative framework and bureaucratic hurdles	-	0	0	+	+	N/D	N/D	0		+	+	N/D	N/D
	Availability of competent support systems	-	-	0	-	-	N/D	N/D	-		-	-	N/D	N/D
	Vulnerability	-	+	0	-	-	N/D	N/D	+		-	-	N/D	N/D
	Complexity	-	+	0	-	-	N/D	N/D	+		-	-	N/D	N/D
	Biological risk	-	+	0	--	--	N/D	N/D	+		--	--	N/D	N/D
	Technological risk: Hazardous substances	-	0	0	0	0	N/D	N/D	0		0	0	N/D	N/D
	Technological risk: Explosions and fires	-	0	0	0	0	N/D	N/D	0		0	0	N/D	N/D
Environment	Global warming	t CO2 eq. / kg 9-cis β-c.	-	-	--	--	+	+	-		-	-	+	+
	Energy resources	GJ / kg 9-cis β-c.	-	-	--	--	+	+	-		-	-	+	+
	Acidification	kg SO2 eq. / kg 9-cis β-c.	-	-	--	--	+	+	0		-	-	+	+
	Eutrophication	kg PO4 eq. / kg 9-cis β-c.	--	-	--	--	+	+	-		-	-	+	+
	Photosmog	kg ethene eq. / kg 9-cis β-c.	-	-	--	-	0	+	0		-	-	+	+
	Ozone depletion	g CFC-11 eq. / kg 9-cis β-c.	-	-	--	-	+	+	0		-	-	++	+
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg 9-cis β-c.	--	-	--	--	+	+	-		-	-	+	+
	Water	-	--	-	-	-	-	-	-		0	0	0	0
	Soil	-	--	-	-	-	-	--	-		0	0	0	0
	Fauna	-	--	-	-	-	-	--	-		0	0	0	0
	Flora	-	--	-	-	-	-	--	-		0	0	0	0
	Landscape	-	-	-	-	-	-	-	0		0	0	0	0
Economy	Operating Expenditure	Million €/year	+	+	+	+	+	++	-		-	-	0	++
	Total Revenue	Million €/year	--	--	-	-	--	--	0		+	+	-	--
	Gross Margin	%	--	-	--	-	--	--	-		-	-	-	--
	Breakeven Revenue	Million €/year	-	+	+	+	--	--	+		0	0	-	--
	Capital Expenditure	Million €	0	0	0	0	++	++	0		0	0	++	++
	Economic Internal Rate of Return (10 years)	%	--	--	--	--	--	--	--		0	0	--	--
	Net Present Value (10 years, 5% discount)	Million €	--	--	--	--	--	--	-		0	0	--	--
Society	Labor rights and decent work	Risk of negative impact/ t 9-cis β-carotene	-	0	--	--	+	-	-		-	-	+	0
	Health and safety		--	-	--	--	--	-	0		-	-	0	-
	Human rights		-	0	--	-	+	+	-		-	-	+	+
	Governance		--	-	--	--	-	-	-		-	-	+	+
	Community infrastructure		+	++	-	+	++	0	-		-	-	+	0

ILCSA results

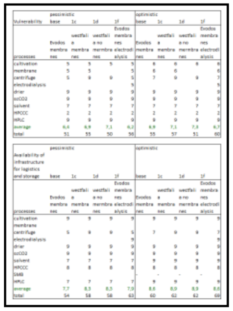
Table 5-5: Comparison of all other scenarios to the benchmark scenario 1 (initial configuration) under optimistic conditions. N/D: no data, N/A: not applicable.

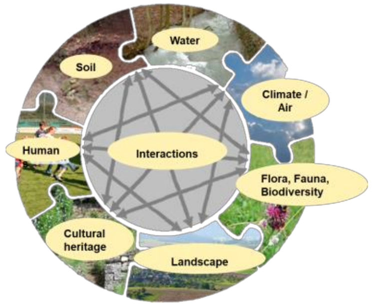
Exemplary results

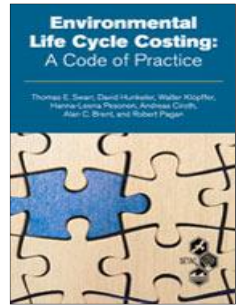
- → No option for an algal product is best in all aspects.
- → Many optimisations increase efficiency with positive impacts on all dimensions of sustainability.
- → Some trade-offs occur. Example: In some cases energy use for additional purifications improves profitability but reduces environmental benefits.
- → Trade-offs need to be identified and managed.
- → …

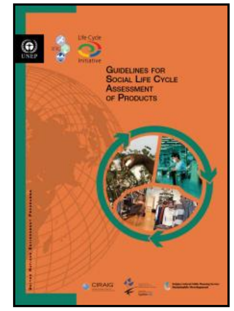
Algae based biofuels: boon or bane?

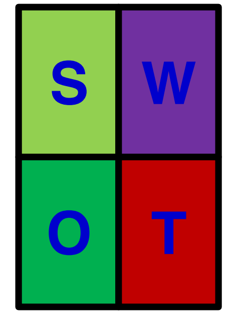
TA	LCA	LC-EIA	LCC	sLCA	SWOT

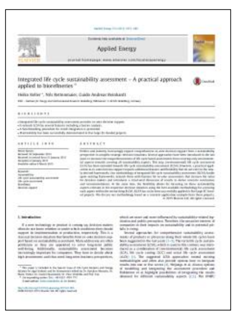












Integrated life cycle sustainability assessment

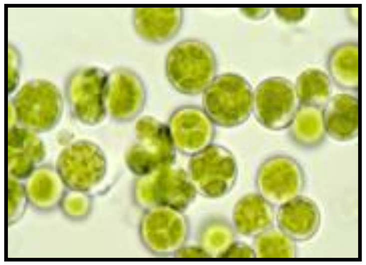
→ Conclusions and recommendations

Lessons learned (1 of 8)

Not all algae based products are sustainable

- **Algae based products are not sustainable just because they are “bio”.**
- **There is a remarkable potential for sustainable algae based products, but they must be developed ...**
  - **in accordance with all sustainability criteria.**
  - **in accordance with other goals towards a sustainable development including alternative use of biomass for electricity and heat generation, and for industry and chemistry.**

Algae



Lessons learned (2 of 8)

Site selection for algae cultivation is crucial

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- ➔ **Do not use arable land –** exceptions subject to conditions.
- ➔ **Guarantee sufficient availability of freshwater –** also if saltwater algae are cultivated.
- ➔ **Go to rural communities if possible** to increase social benefits and reduce costs of land.
- ➔ **Even in Europe, many regions are suitable for algae cultivation –** if heating can be avoided or provided with very low impacts e.g. from waste heat or geothermal.
- ➔ **Take specific requirements of cultivated algae strains into account.**

Lessons learned (3 of 8)

CO_2 for algae cultivation with no or little impacts is required

- E.g. flue gas from a power plant, cement factory or steelworks.
- Still, an extension of the service life of e.g. fossil power plants for algae cultivation is not justified.

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Lessons learned (4 of 8)

Solar power for algae cultivation and processing can reduce impacts decisively

- ➔ **Use as much of your own renewable energy as possible for algae cultivation.**
- ➔ **80 % PV power supply is possible with only 15 % to 50 % additional land occupation.**

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Lessons learned (5 of 8)

Social risks and environmental performance in the value chain need to be managed

- **High social risks are not a no-go but entail obligations. E.g. closely monitor situation to avoid negative social impacts.**
- **Select suppliers according to social and environmental reporting standards such as GRI or EMAS.**

Lessons learned (6 of 8)

Co-product production can make some money and enormously improve land use related environmental burdens

- ➔ **Investigate options to produce co-products next to the main algal product.**
- ➔ **Convert all algae constituents to value-added products.**
- ➔ **Investigate if some biomass streams can be used as feed or even replace animal-based ingredients in novel foods.**

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Lessons learned (7 of 8)

Boundary conditions are important for sustainability

Algae based products are not yet competitive in most cases.

→ **Support development of technologies and market introduction for algae based products with a high positive impact on sustainable development.**

In the future, solar power may compete for land and CCU/CCS may compete for remaining CO_2 sources.

→ **Coordination of policies required.**

> → **Policymakers and consumers can and have to contribute to sustainability, too**

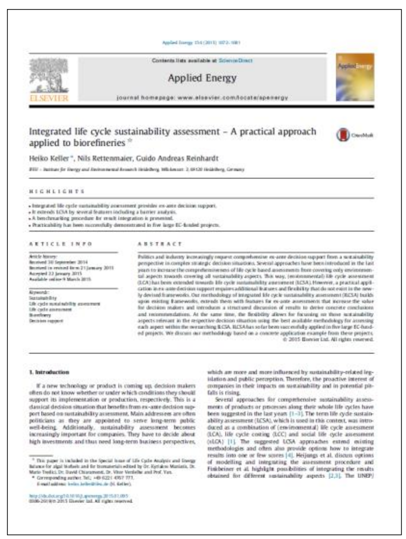
Lessons learned (8 of 8)

Algae cultivation and processing requires high expenditures: improvement necessary.

➔ **Many involved processes still have a substantial potential and need for optimisation – as for any truly innovative technology.**

➔ **Comprehensive life cycle sustainability assessment helps to identify these processes and suitable measures.**

ILCSA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Integrated life cycle sustainability assessment – A practical approach applied to biorefineries

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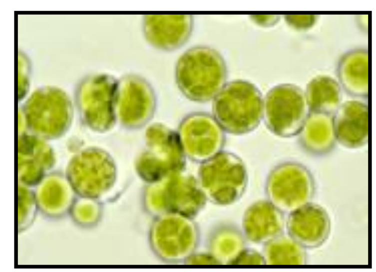
HIGHLIGHTS

ARTICLE INFO

ABSTRACT

Algae



ILCSA: Integrated life cycle sustainability assessment

Thank you very much for your attention

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