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Assessment of Pressure Vessel Manufacturing for Mobile Hydrogen Storage

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Motivation

Sustainable mobility

- Megatrend: urgency & relevance (Golub 2016)
  - Positive and negative sustainability-related impacts from **mobility sector**
  - Challenges & benefits for **industry, society, politics**

- **Mobility Shift** from fossil fuels to alternative drive technologies (Golub 2016, Epstein 2018)
  - Actors **embrace** challenges: developing new technologies & services, assuming social responsibility
  - Decision-makers **lack** understanding of and information on sustainability

! Need for sustainability assessments to support sustainability-oriented decision-making

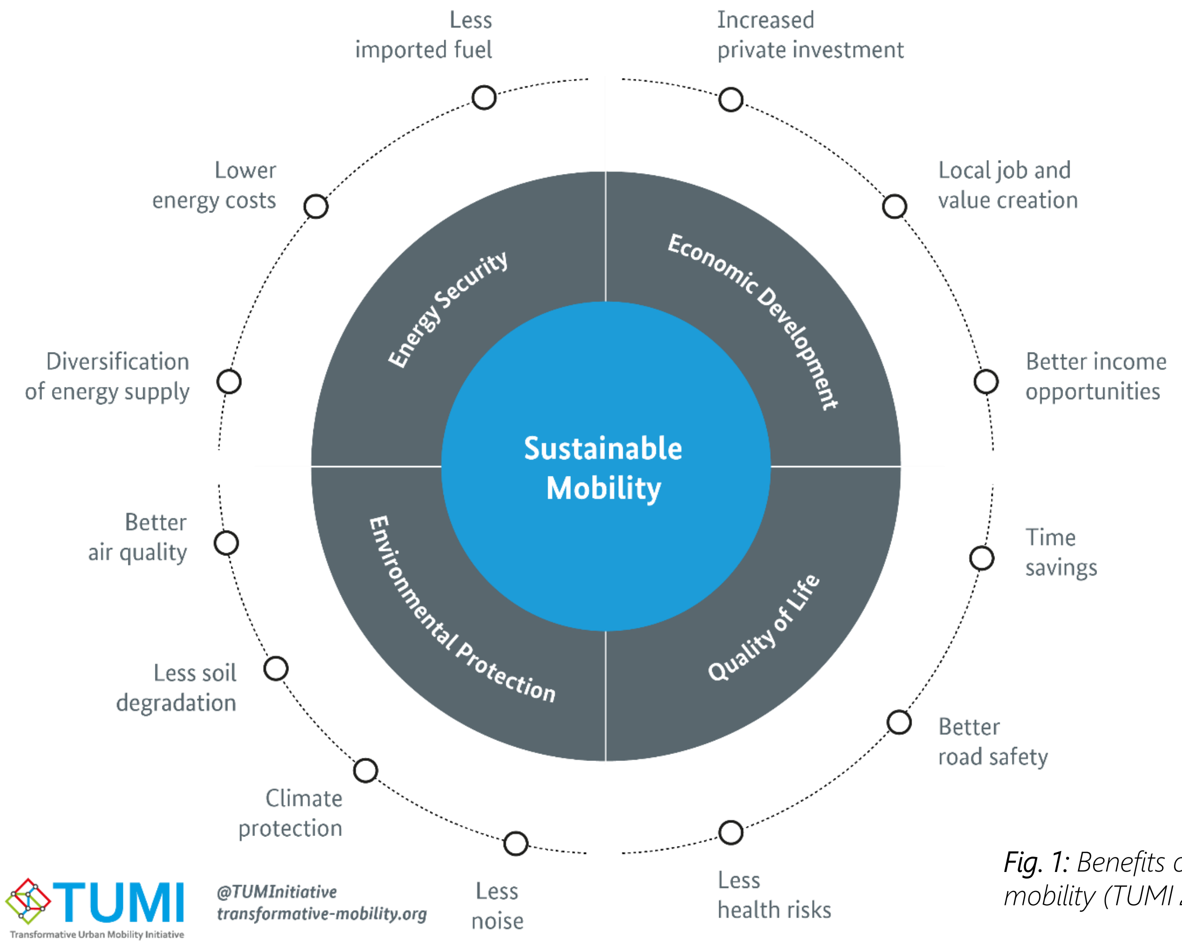


Fig. 1: Benefits of sustainable mobility (TUMI 2019)

Motivation

Fuel cell electric vehicles & pressure vessels for mobile hydrogen storage

- Growing focus on FCEV as alternative drive technology (Staffell et al. 2019)
- Main components of FCEV
  - Hydrogen fuel cell | battery
  - Electric engine | converter
  - **Hydrogen pressure vessel**
- Mobile hydrogen storage
  - Stored in gaseous state (20-70 MPa)
  - **Carbon-fiber reinforced plastic liner**

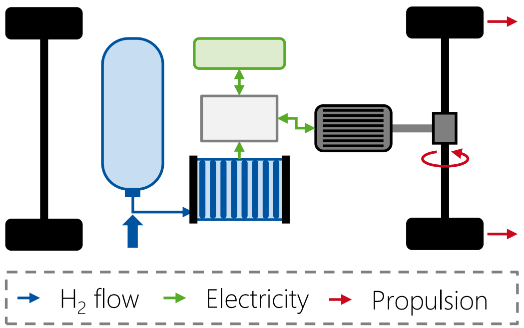


Fig. 2: *FCEV (Adolf et al. 2017; Ehsani et al. 2018)*

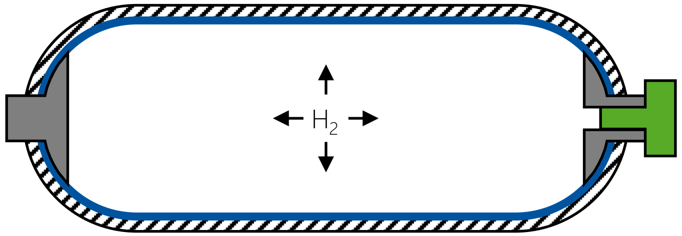


Fig. 3: *Hydrogen pressure vessel (Yamashita et al. 2015; Lengersdorf 2017)*

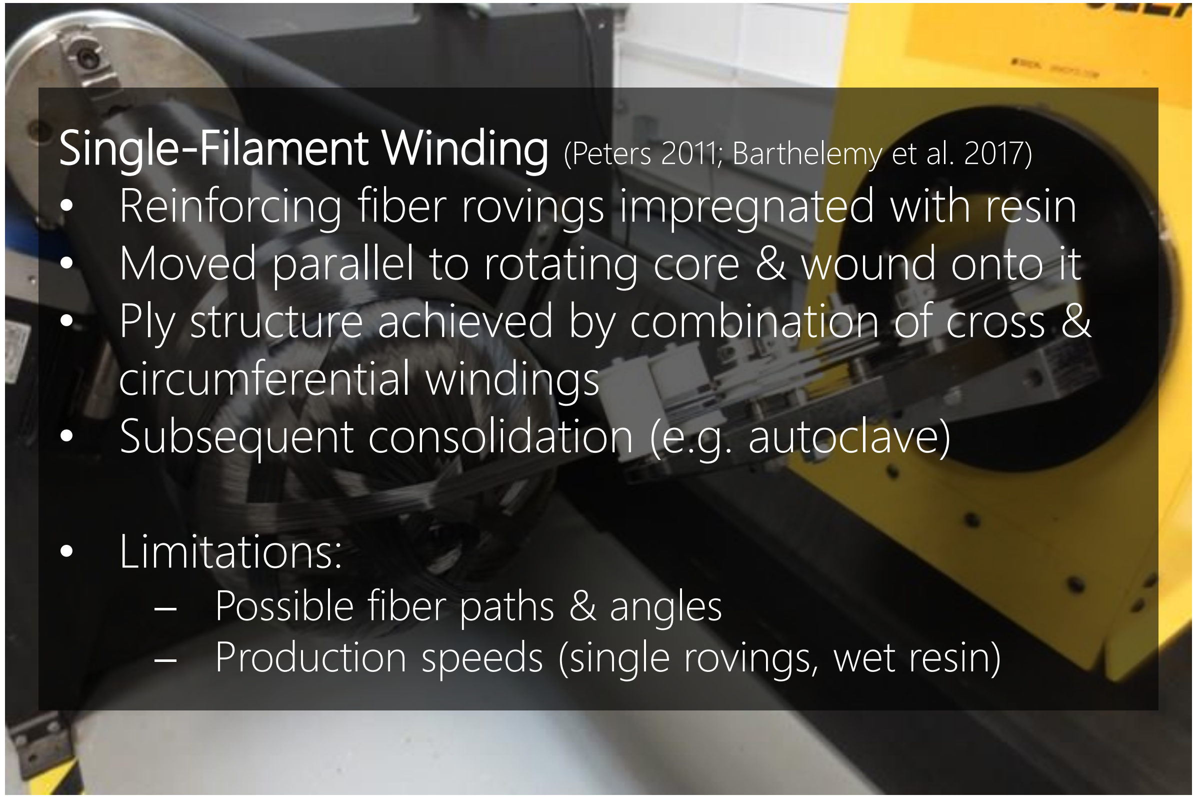
Tab. 1: *Challenges and benefits of FCEV*

Challenges	Benefits
• Indirect emissions from hydrogen (H_2) production (depending on technology) • Elaborate and costly transport (containers, pipelines etc.) • Automotive storage at high pressures (>70 MPa) • High weight of components (fuel cell and storage unit, depending on technology) • High investment and maintenance costs • Weak H_2 infrastructure • Few commercially available vehicles • High safety requirements	• Zero local emissions • Low-emission H_2 production from excess renewable energy possible (power-to-gas) • High energy efficiency (>80 %) • High critical range/fuel economy (depending on storage technology) • Faster re-fueling than BEV, as fast as ICEV • Constant energy supply and performance • Effective method of energy storage • Low health and safety risks

Sources: *(Adolf et al. 2017; Lipman and Weber 2018; Staffell et al. 2019; Shin et al. 2019; Ahmadi et al. 2020)*

Pressure vessel manufacturing for mobile hydrogen storage

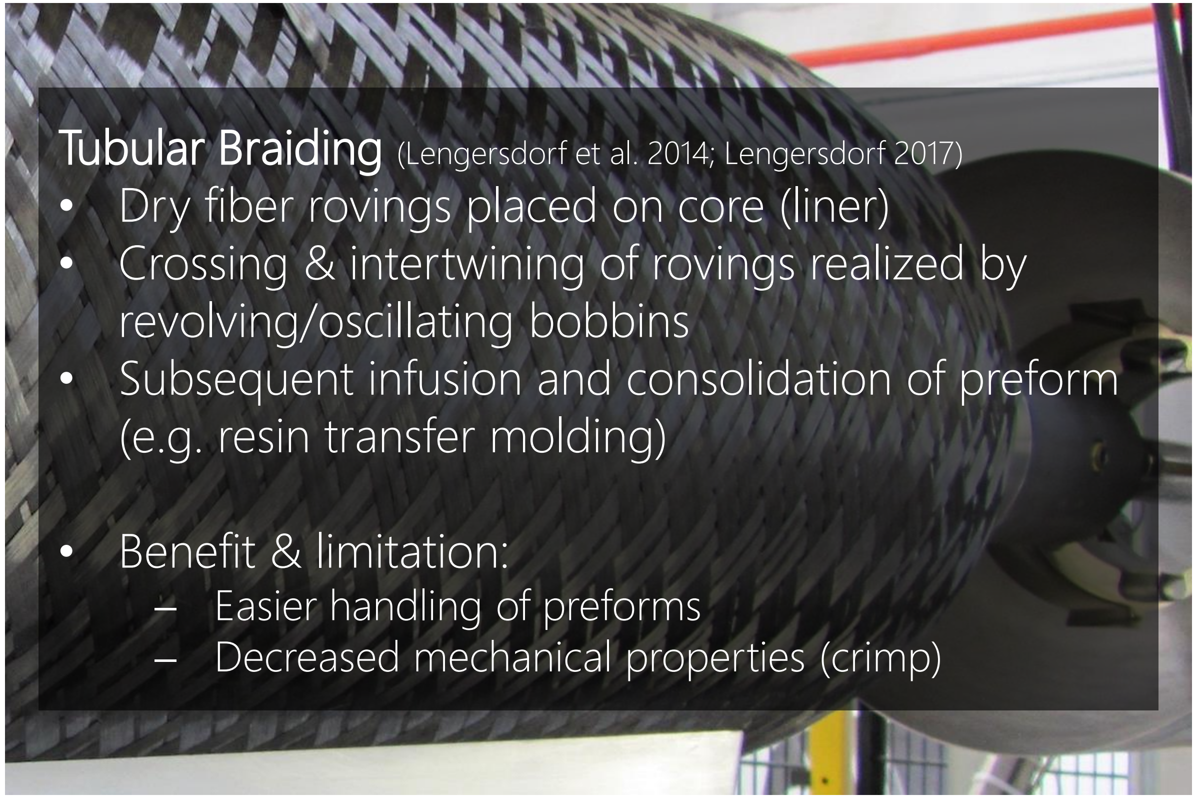
Conventional approaches: Single-Filament Winding & Tubular Braiding Technique



Single-Filament Winding (Peters 2011; Barthelemy et al. 2017)
- Reinforcing fiber rovings impregnated with resin
- Moved parallel to rotating core & wound onto it
- Ply structure achieved by combination of cross & circumferential windings
- Subsequent consolidation (e.g. autoclave)

- Limitations:
  - Possible fiber paths & angles
  - Production speeds (single rovings, wet resin)

Fig. 4: Single-Filament Winding of pressure vessel (Composites World 2020)



Tubular Braiding (Lengersdorf et al. 2014; Lengersdorf 2017)
- Dry fiber rovings placed on core (liner)
- Crossing & intertwining of rovings realized by revolving/oscillating bobbins
- Subsequent infusion and consolidation of preform (e.g. resin transfer molding)

- Benefit & limitation:
  - Easier handling of preforms
  - Decreased mechanical properties (crimp)

Fig. 5: Tubular Braiding of pressure vessel (Moore 2020)

Pressure Vessel Manufacturing for Mobile Hydrogen Storage

Novel approach: Multi-Filament Winding

- Large number of rovings (e.g. 48 or 90) placed simultaneously onto liner
- Processing of dry or pre-impregnated fiber rovings ("tow prepregs")
- Process
  - Rovings guided through iris to winding core
  - Horizontal movement through iris & rotation
  - Rovings pulled off & wound onto core
- Benefits & limitation
  - Significantly higher production speeds
  - Parallel fiber placement (crimp avoidance)

Sources: (Kakita et al. 2014; Uozumi et al. 2015; Murata Machinery Ltd. 2017)

! Need for sustainability-related comparison of manufacturing techniques for mobile hydrogen storage

Vid. 1: Multi-Filament Winding of pressure vessel (IfU & ITA 2019)

Multi-Criteria Sustainability Assessment

Assessment approach: Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle (Fuzzy-IST) (Bitter et al. 2016; 2017)

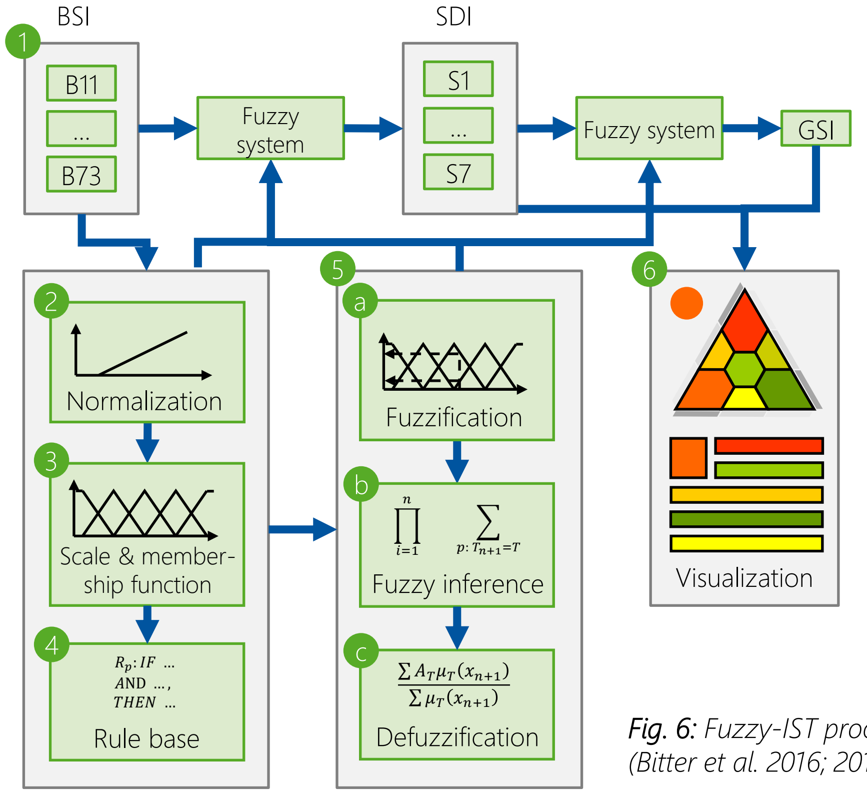


Fig. 6: Fuzzy-IST process (Bitter et al. 2016; 2017)

1. Basic Sustainability Indicators (*BSI*) aggregated stepwise to Sustainability Dimension Indices (*SDI*) & General Sustainability Index (*GSI*)
2. Normalization to increase comparability between different units
3. Fuzzy scales, linguistic terms & triangular membership functions
4. Rule base specifies aggregation (15,835 *IF-THEN* rules)
5. a) Fuzzification: translation of crisp inputs into linguistic terms
   b) Inference: aggregation of indicators based on rule base
   c) Defuzzification: translation back into crisp outputs
6. Visualization via color-coded Integrative Sustainability Triangle

Multi-Criteria Sustainability Assessment

Sustainability indicator-set

- Indicator selection in five consecutive steps:
  - 1. Literature analysis | 2. Pre-selection | 3. Classification based on sustainability dimensions | 4. Review of pre-selection based on expert knowledge | 5. Final selection
- Diverse primary and secondary data sources for quantitative and qualitative indicators with different units

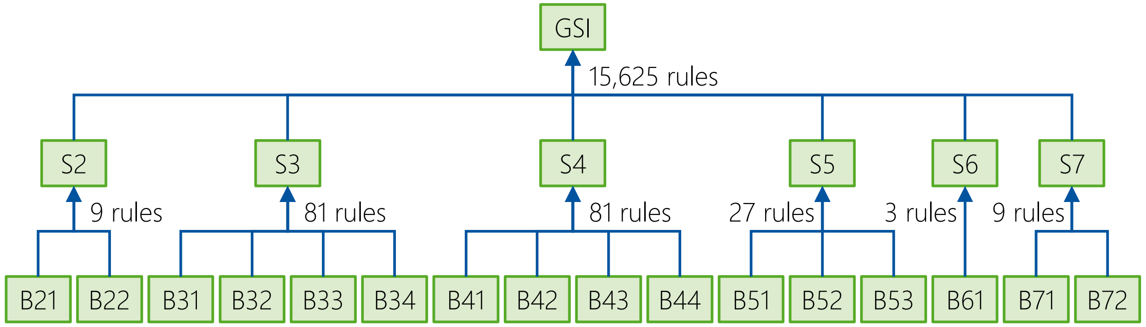


Fig. 7: Aggregation hierarchy of indicator set (Bitter-Krahe 2021)

Tab. 2: Sustainability indicator set (Bitter-Krahe 2021)

Dimension (SDI)	No.	Indicator (BSI)	Unit	Target
Social (S1)	-	-	-	-
Social-environmental (S2)	B21	Greenhouse gas emissions	g/kg	▼
	B22	Soc.-env. criticality of material	Qualitative scale	▼
Environmental (S3)	B31	Amount of waste	m	▼
	B32	Recycling scenario	Discrete scenarios	▲
	B33	Use of recycled material	g	▲
	B34	Prop. of recycled material	%	▲
Environmental-economic (S4)	B41	Energy consumption	Wh/kg	▼
	B42	Resource consumption	g	▼
	B43	Cost efficiency	Euro/s	▼
	B44	Resource costs	Euro/kg	▼
Economic (S5)	B51	Cycle time	min/preform	▼
	B52	Flexibility	Qualitative scale	▲
	B53	Time efficiency	Qualitative scale	▲
Social-economic (S6)	B61	Product quality	%	▼
Social-environmental-economic (S7)	B71	Innovation	Qualitative scale	▲
	B72	Land use	m^2	▼

Legend: ▲ = High indicator value is advantageous, ▼ = Low indicator value is preferable

Multi-Criteria Sustainability Assessment

Input Data

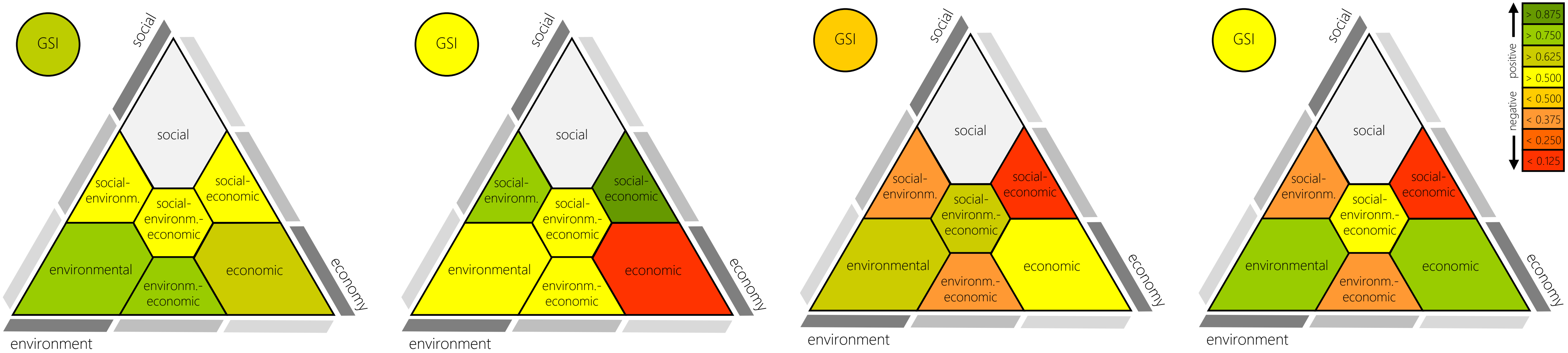
Tab. 3: Input data set (Bitter-Krahe 2021)

No.	Indicator (BSI)	Unit	Single-Filament Winding (SFW)	Tubular Braiding Technique (BT)	Multi-Filament Winding 48 (MFW-48)	Multi-Filament Winding 90 (MFW-90)	Source(s)
B21	Greenhouse gas emissions	g/kg	300.75	398.47	491.35	501.41	[1, 2, 8]
B22	Socio-environmental criticality of material	Qualitative scale	5	1	3	3	[3]
B31	Amount of waste	m	10.00	64.00	48.00	90.00	[1, 3]
B32	Recycling scenario	Discrete scenarios	1	1	1	1	[6, 7]
B33	Use of recycled material	g	1440.00	1440.00	1440.00	1440.00	[1]
B34	Proportion of recycled material	%	51.80	51.20	52.30	53.50	[1]
B41	Energy consumption	Wh/kg	750.00	993.70	1225.30	1250.41	[1, 2, 5, 4]
B42	Resource consumption	g	1337.00	1375.00	1312.00	1250.00	[1]
B43	Cost efficiency	Euro/s	0.28	0.91	1.37	2.56	[1–3]
B44	Resource costs	Euro/kg	40.00	40.00	60.00	60.00	[2, 3]
B51	Cycle time	min/preform	2.50	3.50	1.50	1.00	[1-3]
B52	Flexibility	Qualitative scale	7	5	5	6	[3]
B53	Time efficiency	Qualitative scale	5	3	6	7	[3]
B61	Product quality	%	2.00	1.00	3.50	3.50	[1]
B71	Innovation	Qualitative scale	5	4	6	7	[3]
B72	Land use	m^2	28.50	25.50	36.50	55.50	[2, 3]

Sources: [1] = Primary data from experiments in How2MultiWind; [2] = Material/machine data sheets; [3] = Expert estimation (How2MultiWind project team and user committee); [4] = (Suzuki and Takahashi 2005); [5] = (Song et al. 2009); [6] = (Bundestag 2012); [7] = (Ribeiro et al. 2016); [8] = (Icha and Kuhns 2020)

Multi-Criteria Sustainability Assessment

Visualization of results & comparison of manufacturing approaches



(a) Single-filament winding

(b) Tubular braiding technique

(c) Multi-filament winding 48 rovings (laboratory)

(d) Multi-filament winding 90 rovings (industry)

Fig. 8: Visualized results of Fuzzy-IST assessment for pressure vessel manufacturing approaches (Bitter-Krahe 2021)

Multi-Criteria Sustainability Assessment

Interpretation of assessment results

- Ranking of alternatives (relative assessment)
- Single-Filament Winding
  - No critical sustainability dimension (medium to high scores)
  - Strengths in environmental & environmental-economic (*low waste*)
  - Weakness in social-environmental (*high criticality of material - resin*)
- Multi-Filament Winding
  - Critical in social-economic dimension (*low product quality - porosity*)
  - Strengths in environmental & economic (*high % of recycling material, low cycle time, high efficiency*)
  - Weaknesses in social-environmental & environmental-economic (*high GHG-emissions, energy consumption & resource costs*)

Tab. 4: Assessment results (Bitter-Krahe 2021)

No.	SDI/GSI	SFW	BT	MFW-48	MFW-90
S2	Social-environmental	0.500	0.756	0.275	0.250
S3	Environmental	0.750	0.500	0.740	0.750
S4	Environmental-economic	0.750	0.503	0.287	0.250
S5	Economic	0.700	0.000	0.525	0.750
S6	Social-economic	0.600	1.000	0.000	0.000
S7	Social-environ-mental-economic	0.617	0.500	0.650	0.500
GSI	General sustain-ability index	0.645	0.500	0.497	0.500
	Ranking	1	2	4	2

positive	> 0.875
	> 0.750
	> 0.625
	> 0.500
negative	< 0.500
	< 0.375
	< 0.250
	< 0.125

Summary & Outlook

Summary

- **Single-Filament Winding** (state of the art) is currently most sustainable manufacturing alternative
- No strict dominance between alternatives
  - Different strengths and weaknesses (BSI & SDI level)
  - Low variance between GSI values (0.497 – 0.645)
- Multi-Filament Winding & Tubular Braiding Technique require further **research & development**
  - Some potentials on BSI & SDI level
  - Lower maturity levels than Single-Filament Winding
  - Especially **MFW-90** is promising (issue: *product quality*)

Outlook

- Starting points for improvements for Multi-Filament Winding:
  - Improve energy consumption/efficiency & GHG-emissions
  - Investigate alternative materials (pre-impregnated rovings)
  - Reduce waste from manufacturing process
  - Investigate approaches to increase product quality (porosity)
  - Decrease machine size (*land use*)
- Further research potentials
  - Re-assessment of alternatives after **improvements**
  - Realize **absolute** sustainability assessment of alternatives (*how do they contribute to sustainable development?*)
  - Sustainability assessment of **entire life cycle** of pressure vessels for mobile hydrogen storage & FCEV

References

Literature & figure sources (1/2)

- Adolf J, Balzer CH, Louis J, et al (2017) Energie der Zukunft? Nachhaltige Mobilität durch Brennstoffzelle und H2: Shell Wasserstoff-Studie (Energy of the Future? Sustainable Mobility via Fuel Cell and H2: Shell Hydrogen Study). Shell Deutschland; Wuppertal Institut, Hamburg, Germany
- Ahmadi P, Torabi SH, Afsaneh H, et al (2020) The effects of driving patterns and PEM fuel cell degradation on the lifecycle assessment of hydrogen fuel cell vehicles. International Journal of Hydrogen Energy 45:3595–3608. https://doi.org/10.1016/j.ijhydene.2019.01.165
- Barthelemy H, Weber M, Barbier F (2017) Hydrogen storage: Recent improvements and industrial perspectives. International Journal of Hydrogen Energy 42:7254–7262. https://doi.org/10.1016/j.ijhydene.2016.03.178
- Bitter J, Printz S, Lahl K, et al (2016) Approach to Sustainability Assessment of Renewable Energy Technologies combining Fuzzy Logic with the Integrative Sustainability Triangle. IJSED 5:252–262. https://doi.org/10.20533/ijsed.2046.3707.2016.0033
- Bitter J, Printz S, Lahl K, et al (2017) Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle - An Application for a Wind Power Plant. International Journal of Contemporary Energy 3:50–61
- Bitter-Krahe J (2021) Situation-Oriented Approach Selection for Sustainability Assessments. Doctoral Thesis, RWTH Aachen University
- Bundestag (2012) Act to Promote Circular Economy and Safeguard the Environmentally Compatible Management of Waste (KrWG)
- Composites World (2020) Part 2: Performance and safety benefits of prepregs. In: Composites World. https://www.compositesworld.com/articles/part-2-performance-and-safety-benefits-of-prepregs. Accessed 28 Mar 2021
- Ehsani M, Gao Y, Longo S, Ebrahimi K (2018) Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, 3rd edn. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA
- Epstein MJ (2018) Making Sustainability Work: Best Practices in Managing and Measuring Corporate Social, Environmental and Economic Impacts, 1st edn. Routledge, London, UK
- Golub A (2016) Mobility and Sustainability. In: Heinrichs H, Martens P, Michelsen G, Wiek A (eds) Sustainability Science: An Introduction, 1st edn. Springer Netherlands, Dordrecht, Netherlands, pp 261–272
- Icha P, Kuhns G (2020) Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 - 2019 (Development of the specific carbon dioxide emissions of the German electricity mix in the years 1990 - 2019). Umweltbundesamt, Dessau-Roßlau, Germany
- Institut für Unternehmenskybernetik (IfU) e.V., Institut für Textiltechnik (ITA) der RWTH Aachen University (2019) Multi-Filament Winding of pressure vessel. Aachen, Germany

References

Literature & figure sources (2/2)

- Kakita Y, Hirose M, Nakai A, et al (2014) Fabrication and Mechanical Properties of Noncrimp CFRP Pipe by Braiding Technique. Design, Manufacturing and Applications of Composites 2014
- Lengersdorf M (2017) Produktorientiertes Geflecht-Preforming für Druckbehälter in Faserverbundbauweise (Product-oriented braided pre-preforming for pressure vessels in fiber composite construction). Doctoral Thesis, RWTH Aachen University
- Lengersdorf M, Multhoff J, Gries T (2014) Braiding: A New Production Method Approach for Composite Pressure Vessels in Automotive Applications. American Society of Mechanical Engineers Digital Collection, Anaheim, CA, USA
- Lipman TE, Weber AZ (eds) (2018) Fuel cells and hydrogen production, 2nd edn. Springer Reference, New York, NY, USA
- Moore S (2020) Self-closing HP-RTM Molds Shape Hydrogen Tanks. In: Plastics Today. https://www.plasticstoday.com/automotive-and-mobility/self-closing-hp-rtm-molds-shape-hydrogen-tanks. Accessed 28 Mar 2021
- Murata Machinery Ltd. (2017) Outstanding performance of Multiple-supply FW
- Peters ST (ed) (2011) Composite filament winding, 1st edn. ASM International, Materials Park, OH, USA
- Ribeiro M, Fiúza A, Ferreira A, et al (2016) Recycling Approach towards Sustainability Advance of Composite Materials' Industry. Recycling 1:178–193. https://doi.org/10.3390/recycling1010178
- Shin J, Hwang W-S, Choi H (2019) Can hydrogen fuel vehicles be a sustainable alternative on vehicle market? Comparison of electric and hydrogen fuel cell vehicles. Technological Forecasting and Social Change 143:239–248. https://doi.org/10.1016/j.techfore.2019.02.001
- Song YS, Youn JR, Gutowski TG (2009) Life cycle energy analysis of fiber-reinforced composites. Composites Part A: Applied Science and Manufacturing 40:1257–1265. https://doi.org/10.1016/j.compositesa.2009.05.020
- Staffell I, Scamman D, Velazquez Abad A, et al (2019) The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science 12:463–491. https://doi.org/10.1039/C8EE01157E
- Suzuki T, Takahashi J (2005) Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass-Produced Passenger Cars. In: Proceedings of the 9th Japan International SAMPE symposium. pp 14–19
- Transformative Urban Mobility Initiative (TUMI) (2019) Benefits of Sustainable Mobility. In: Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Benefits_of_Sustainable_Mobility.png. Accessed 28 Mar 2021
- Uozumi T, Ohtani A, Nakai A, et al (2015) Non-crimp Tubular Preforming with Automation System and High Productivity. Journal of Mechanics Engineering and Automation 5:435–439. https://doi.org/10.17265/2159-5275/2015.08.002
- Yamashita A, Kondo M, Goto S, Ogami N (2015) Development of High-Pressure Hydrogen Storage System for the Toyota "Mirai"

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