Repository

Section 15 - Hydrogen, Sustainability & Circularity

Topic 100 - Life Cycle Thinking & End-of-Life Strategies (R-Strategies)

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1. Repository Introduction

This document is part of the H2VE Repository, a structured collection of learning resources and materials developed to support Centres of Vocational Excellence (CoVEs) and training providers in delivering high-quality, up-to-date hydrogen education. The thematic clusters and sub-topics covered in this repository were jointly compiled by all H2VE project partners as part of Deliverable D5.1 - Educational Training Material Specification Document. Each document corresponds to a specific sub-topic within a broader thematic cluster and follows a standardized structure comprising a document header, learning context, core content, curated digital tools, and assessment guidance, where applicable. The aim is to provide trainers and educators with general resources as well as modular content that can be integrated into existing curricula or adapted to specific training contexts. A list of underlying resources and sources is provided at the end of each document to allow for further exploration and verification of the material presented.

2. Topic Overview

Life cycle thinking provides the conceptual foundation for assessing the environmental performance of hydrogen technologies across their entire lifespan, from raw material extraction to end-of-life. This topic presents the R-strategies framework (e.g., Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) as a structured approach to minimizing resource use and waste at each stage of the hydrogen value chain. Learners are introduced to how these strategies apply specifically to hydrogen components such as electrolyzers, fuel cells, and storage tanks, and how prioritizing higher-order R-strategies (e.g., reuse over recycling) can reduce the overall environmental footprint. The aim is to equip learners with the conceptual tools needed to evaluate end-of-life options and to understand how life cycle thinking informs circular design decisions upstream.

3. Learning Resource Overview

1. Learning Context	Prerequisites: • Completed Topic 99 (Sustainability Criteria & Supply Chain) or equivalent knowledge • Basic familiarity with the concept of a product's 'life cycle' from raw material to disposal

2. Content	• **Life Cycle Thinking vs. Life Cycle Assessment** Life Cycle Thinking (LCT) is a qualitative, systems-oriented way of considering a product's impacts from raw material to disposal, used to guide design and strategic decisions. Life Cycle Assessment (LCA) is the quantitative, ISO-standardised methodology that formally measures those impacts. LCT typically precedes and frames a full LCA rather than replacing it. • **The 10R Hierarchy (Potting et al., 2017)** The framework ranks circular strategies from R0 to R9 - Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover - in descending order of value retention. Lower R-numbers keep more of a product's original value and material integrity intact; higher R-numbers represent a closer approach to end-of-life disposal. • **Mapping to the EU Waste Framework Directive** The EU's legal waste hierarchy (prevention, reuse, recycling, recovery, disposal) is a coarser regulatory expression of the same logic as the 10R framework, providing the legal basis that underpins circular economy practice in Europe. • **Applying R-Strategies to Hydrogen Equipment** Which R-strategy fits best depends on the component: Membrane Electrode Assemblies degrade chemically and are typically suited to recycling or recovery, while more durable components such as bipolar plates, end plates, and balance-of-plant parts retain higher value and are better candidates for reuse, repair, or refurbishment.
3. Digital Tools	• FCH-LCA Tool, End-of-Life Modelling Templates: The FCH-LCA Tool includes end-of-life system templates for Hydrogen equipment. Use to model R3–R9 scenarios quantitatively.
4. Assessment Guidance	**Assessment Methods** • Component mapping exercise: students receive a PEMFC stack diagram and assign an R-strategy to

	each component layer, justifying their choice in 2–3 sentences. • Short quiz (10 multiple-choice): test recall of the R-hierarchy and the distinction between LCT and LCA. **Sample Questions** 1. Define Life Cycle Thinking and explain how it differs from a formal Life Cycle Assessment. 2. Place the following strategies in order from highest to lowest value retention: Recycle, Remanufacture, Repair, Recover, Reuse. 3. A PEM electrolyser stack reaches end-of-life after 80,000 hours. The membrane electrode assembly is degraded but the titanium end plates are intact. Which R-strategies would you recommend for each component and why? **Evaluation Criteria** • Correct ordering and definition of R-strategies (30%) • Appropriate application of R-strategies to specific H_2 components (50%) • Quality of justification referencing value retention and technical feasibility (20%)
5. References	Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular economy: Measuring innovation in the product chain. PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/en/publications/circular-economy-measuring-innovation-in-the-product-chain Uekert, T., et al. (2024). Electrolyzer and fuel cell recycling for a circular hydrogen economy. Advanced Sustainable Systems. https://docs.nrel.gov/docs/fy24osti/87146.pdf (Open access) Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221–232. Grow Circular: 9R Framework Knowledge Base: EU Grow Circular project. Defines all 9/10 R-strategies with examples. Use as a student reference card.

	Circularise: R-Strategies for a Circular Economy: Illustrated overview of all 10 R-strategies with real-world examples. Suitable as student handout or pre-reading.