INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON




# Ecologie industrielle et économie circulaire

## GI-4-S2-EC-EIE 2026-27

## 1. Definitions

membre de UNIVERSITÉ DE LYON

# Course Objectives

- Don't talk about the problems because we will only detail them for you more, but you already know them

- *Focus on solutions*:
  - *offered by the Industrial Engineering*:
    - Op. Reasearch, in part. *multi-objective optimization (lexicographic with ε-constraint to find Pareto front)*
    - Multi-criteria decision making (ELECTRE I, II and II, AHP, Prometheus, etc.)
    - *Closed-loop supply chain*,
    - etc.

  - Concepts: Moving from the linear to the circular economy = *Closing Material/Energy Loops*
    ≈ (≠ because >) *Turning waste into resources*

  - Flow Modeling Tools:
    - LCA (LifeCycle analysis) : seen in 3GI
    - Social LCA(SLCA= Social LCA) : equality ♂/♀, CSR, urban impact, Diseases due to overconsumption
    - MFA (Material Flow Analysis)
      - with data reconciliation (correction of measurements using the system model)

    => These tools provide ≠ points of view of the same reality: *Product (LCA) vs. Production (MFA)*

  - DDRS Dedicated Courses = transversal (≠ disciplinary) => Simple tools (we're going to use Excel and its solver)

# Today

1. *Overview of the 14 sessions*
2. Context
3. Definitions
4. Exercises

Thanks to Anna Havukainen (2021-22 LUT University exchange – Lappeenranta-Lahti University of Technology – Finland) for her help in the creation of this course

# Content

| 4GI1 | | 4GI2 | | 4GI3 | |
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| 1 Définitions | Taha | 1 Definitions | Taha | 1 Définitions | Thierry |
| 2 Déchets – Lois | Vincent | 2 Waste – Laws | Vincent | 2 Déchets – Lois | Vincent |
| 3 Déchets – MTD | Vincent | 3 Waste – BAT | Vincent | 3 Déchets – MTD | Vincent |
| 4 Jeu In the Loop | Taha | 4 Game In the Loop | Taha | 4 Jeu In the Loop | Thierry |
| 5 Débrief jeu + Ecoparcs cours | Taha | 5 Game Debrief + Ecoparks | Taha | 5 Débrief jeu + Ecoparcs cours | Thierry |
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| 8 TD *MFA* | Taha | 8 *MFA* | Taha | 8 TD *MFA* | Thierry |
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| 10 TP *MFA* réc. d. & MFA bi-obj. | Taha | 10 Lab *MFA* Data recon. + Bi-obj | Taha | 10 TP *MFA* réc. d. & MFA bi-obj. | Thierry |
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| 13 Economie circulaire dans l'industrie pneumatique | Cyril | 13 Circular economy in tire industry | Cyril | 13 Economie circulaire dans l'industrie pneumatique | Cyril |
| 14 Déchets – Bâtiments | Fiona | 14 Building Waste | Fiona | 14 Déchets – Bâtiments | Fiona |

Grading: 100% ratio = A2 (eco-park + Reverse logistics on Rebooteille) + Report/Excel file of the labs

# Sessions 2 & 3 Waste (classroom)

2. 1 session on generalities (technical and legal aspects for recycling waste)
3. 1 session on BAT (Best Available Techniques)

} Vincent

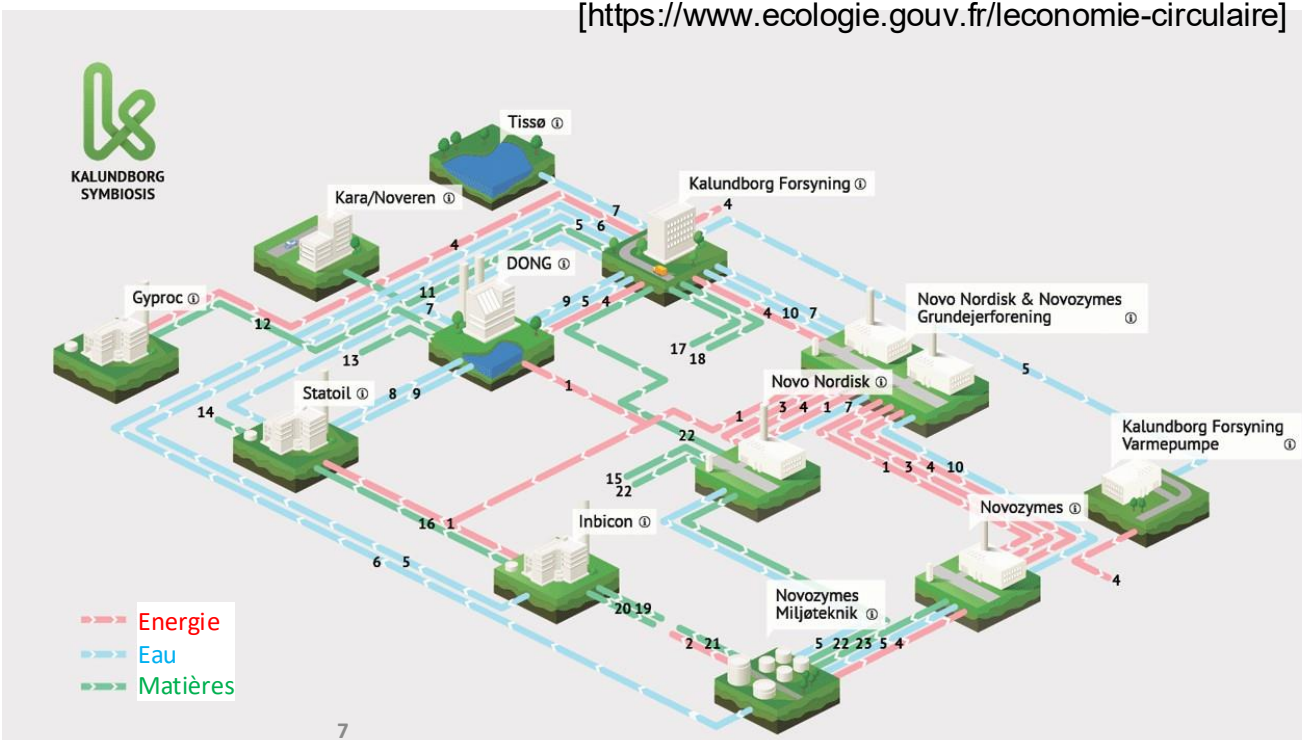
# Session 4. In the Loop Game (classroom)

https://intheloopgame.com

**Industrial and territorial ecology**: Synergize and pool the flows of materials, energy, water, infrastructure, goods or services between several economic actors in order to optimize the use of resources in a territory.

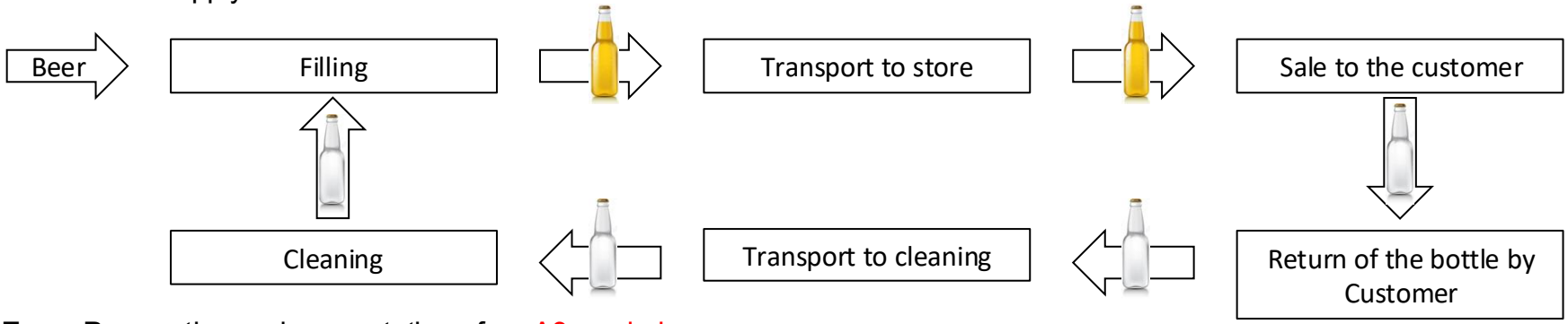
[https://www.ecologie.gouv.fr/leconomie-circulaire]

Exo. : *A3 graded on an eco-park compared to Kalundborg*




[https://circulareconomy.europa.eu/platform/en/good-practices/kalundborg-symbiosis-six-decades-circular-approach-production]

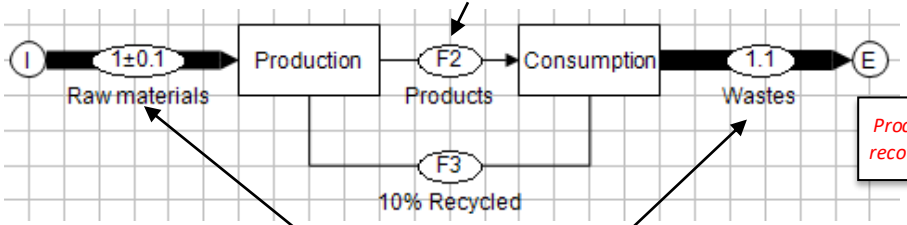
- Example of returnable bottles (reuse) by Rebooteille
- Recycling a bottle saves only 20% of the energy
- Circularized supply chain for beer bottles:




- Exo. : Preparation and presentation of an A3 graded on:
  1. Demand/Supply Forecast
  2. Refurbishment (washing and sorting) & management of the supplier relationship (choice of glues, bottle shape, etc.)
  3. Evaluating sustainable performance
  4. Transport management (optimisation of truck loading, route planning, etc.)
  5. Information Systems
  6. Network design (sizing & localization)

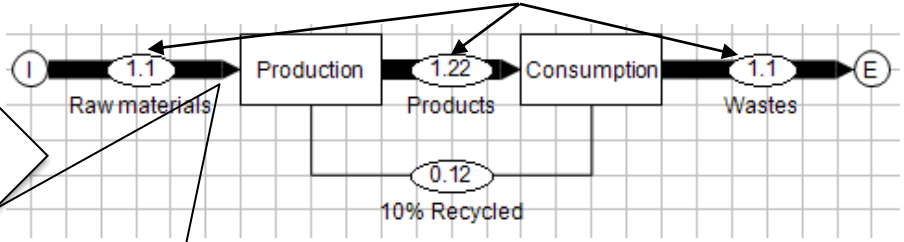
# Sessions 8 (classroom) and 9, 10 & 11. (lab) MFA = Material Flow Analysis

Flow F2 and F3 unmeasured




2 Measured flows

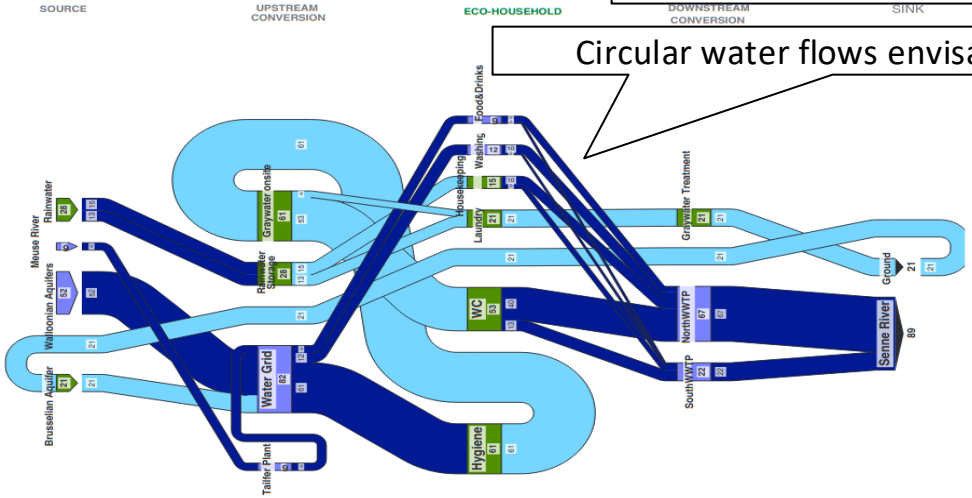
4 flux inférés par réconciliation de données




*Process data reconciliation*

Sankey diagram : Thickness of the deflection proportional to the % of the flow

Circular water flows envisaged for Brussels






Tool: Linear algebra with single- and then bi-objective optimization

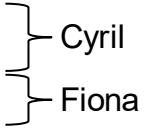
[United Nations Environment Programme (2019) « Brussels Capital Region: Circular Economy Transition », https://resourceefficientcities.org/wp-content/uploads/2019/10/GI-REC-Pilot-City-Brussels-FINAL.pdf]

# Session 12. Disassembly lab (PC room)

- Planning of disassembly operations with variable quality
- *Graded report and Excel file*

# Sessions 13 & 14 (classroom)

13. 1 session on the circular economy in the tire industry
14. 1 session on building waste



# Today

1. Overview of the 14 sessions
2. *Context*
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Some proposed solutions to the environmental crisis:

- Documents :
  - Working group 3 of GIEC [GIEC, Sixth Assessment Report, "Climate Change 2022: Mitigation of Climate Change", www.ipcc.ch/report/sixth-assessment-report-working-group-3]
  - French Economy Transformation Plan [Shift Project, 2022, https://theshiftproject.org/article/ptef-livre-et-site-web]
  - Energy futures 2050: Electricity production scenarios to achieve carbon neutrality in 2050 [RTE, 2021, www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques]
  - NegaWatt [https://negawatt.org/Scenario-negaWatt-2022]
- Approaches :
  - Individual (behavioural) and/or collective (laws and companies) changes
  - Sobriety/degrowth
  - Techno-solutionism :
    - Existing : - *circular economy* (of which eco-design and Industrial and Territorial Ecology)
      - Bio-sourced products
      - Planting trees
      - …
    - Hoped : - capting $CO_2$
      - nuclear fusion
      - …

=> *When technical solutions exist, engineers must be ready* when states and companies are looking for these solutions (cf. shortage of people trained in LCA vs. strong growth in demand for LCA)

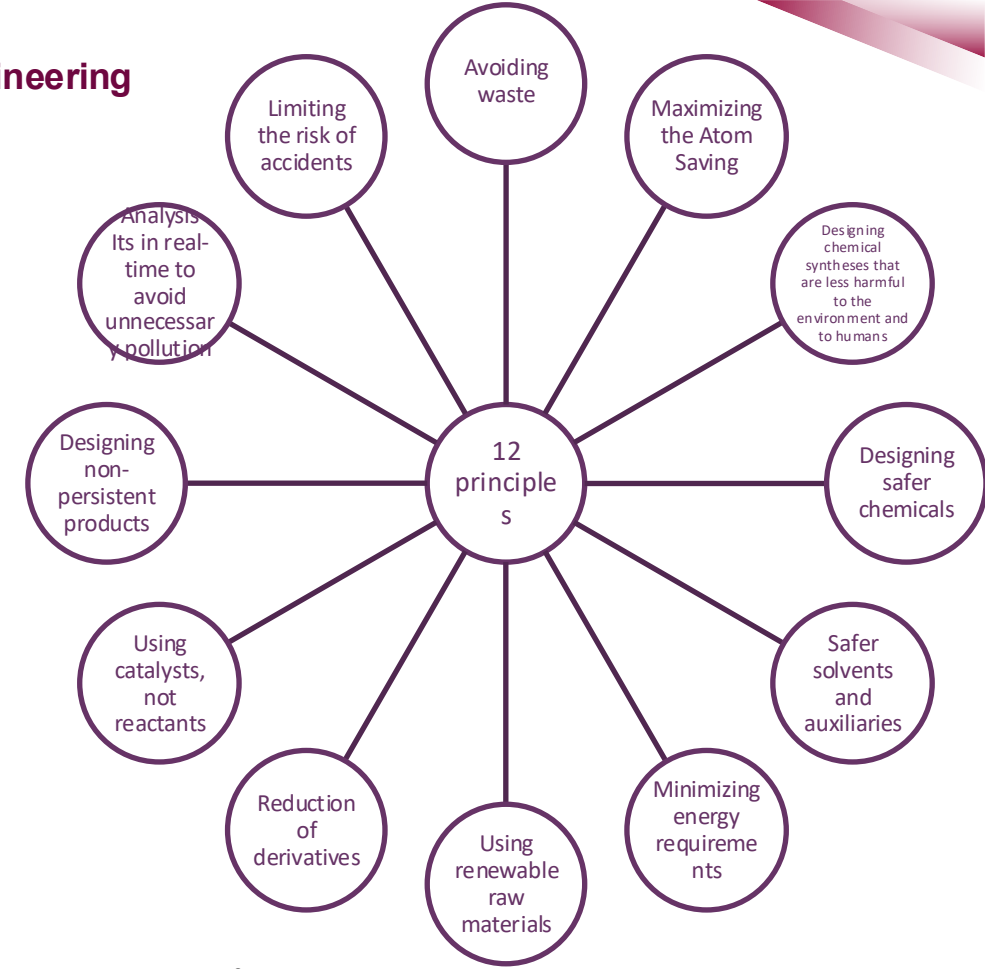
# Constraint optimization has always been the work of engineers

From QCD to QCDES:

- Engineers are already used to optimizing under constraints: QCD Indicators (It's not just the C price that matters)
  - SRFI can be seen as a simple addition of criteria : QCDMS where
  - *E=environment*, e.g. indicators of an LCA (eutrophication of the cells, eco-toxicity, ionizing radiation, etc.). and of course CO2)
  - S often stands for security, but we can broaden it to social and societal
- *Good news*, We have methods for making decisions with a lot of criteria:
  - Not complicated to go from 1 to 2 criteria: Pareto front (*cf. session 12*)
  - Not complicated to go from 2 to 3 criteria: 3D QCD Pareto Front projected onto your 2D sheet
  - Very complicated to go from 3 to 4 criteria: Multi-Objective Optimization (NSGA-II, ε-constraint…) and Multi-criteria methods (AHP, ELECTRE I,II&III, PROMETHEE…)
  - … … … (*cf. 5GI*)
  - Very easy to go from 4 to 55 criteria: Same multi-objective optimization and multi-criteria methods

# Primum non nocere : 12 Principles of Green Engineering

1. **Inherent Rather Than Circumstantial**
   Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.
2. **Prevention Instead of Treatment**
   It is better to prevent waste than to treat or clean up waste after it is formed.
3. **Design for Separation**
   Separation and purification operations should be designed to minimize energy consumption and materials use.
4. **Maximize Efficiency**
   Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5. **Output-Pulled Versus Input-Pushed**
   Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
6. **Conserve Complexity**
   Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7. **Durability Rather Than Immortality**
   Targeted durability, not immortality, should be a design goal.
8. **Meet Need, Minimize Excess**
   Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
9. **Minimize Material Diversity**
   Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10. **Integrate Material and Energy Flows**
    Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
11. **Design for Commercial "Afterlife"**
    Products, processes, and systems should be designed for performance in a commercial "afterlife."
12. **Renewable Rather Than Depleting**
    Material and energy inputs should be renewable rather than depleting




[Anastas P. T. & Zimmerman J. B. (2003) « Design through the 12 principles of green engineering », Environmental Science & Technology, 37(5), doi: 10.1021/es032373g] [http://greenchemistry.yale.edu/about/principles-green-engineering] [https://www.techniques-ingenieur.fr/actualite/articles/solvants-et-chimie-verte-les-solvants-en-chimie-organique-13-25261/]

# Equation of Kaya

- $$CO_2 = CO_2$$
$$CO_2 = \frac{CO_2}{Tep} Tep$$
$$CO_2 = \frac{CO_2}{Tep} \frac{Tep}{PIB} PIB$$
$$CO_2 = \frac{CO_2}{Tep} \frac{Tep}{GDP} \frac{GDP}{Pop} Pop$$



- $CO_2$ = Energy nuisance (tons$_{CO2}$/Watt.hour) x Energy intensity (Watt.hour/€) x Purchasing power (€/person) x Population (Number of people)
- Is the nature of these quantities the same??

- On which part(s) of the equation should we act to limit global warming to 2°C: $CO_2^{2050} = {}^{CO_2^{2010}}/_3$? What difficulty(ies) and/or consequences?

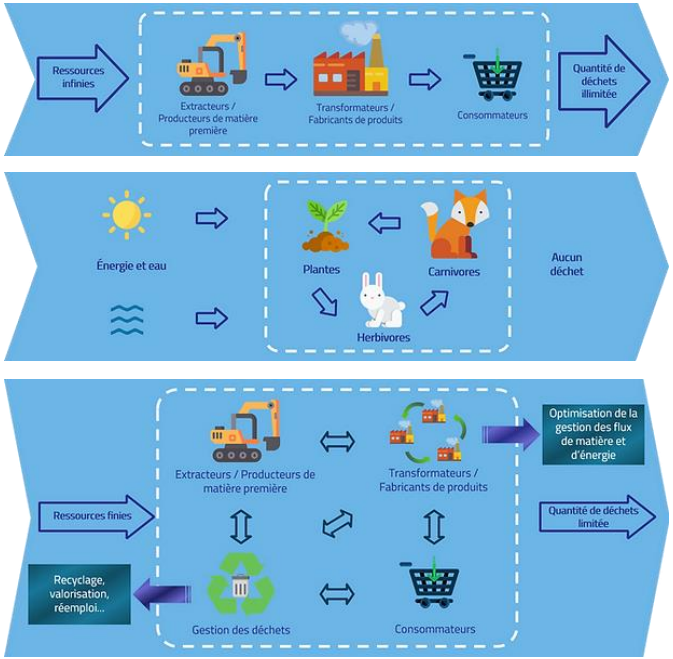
[Menecier S., « L'équation de Kaya », cours UVED, https://www.uved.fr/fiche/ressource/lequation-de-kaya]

# Today

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# Circular economy = Linear economy + ecosystem/symbiosis

- Linear operation of conventional industrial systems
- Functioning of natural ecosystems
- Circular operation of industrial ecosystems



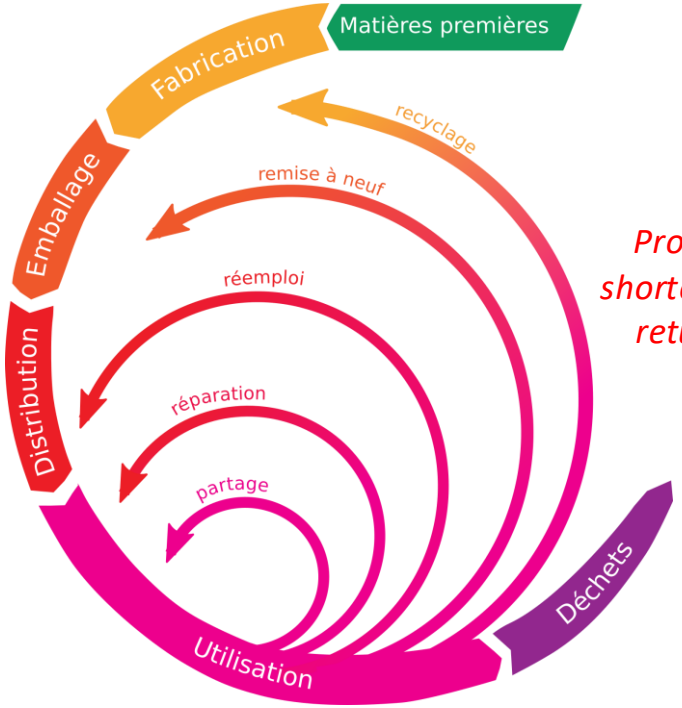

[Figure of Club d'Ecologie Industrielle de l'Aube, www.ceiaube.fr/presentation-ecologie-industrielle]

# Circular economy

The circular economy consists of producing goods and services in a sustainable way by limiting the consumption and waste of resources and the production of waste. It is a question of moving from an all-disposable society to a more circular economic model.
[https://www.ecologie.gouv.fr/leconomie-circulaire, 2020]

The 8 R's of the circular economy:

- *Rethink/*Repenser le besoin (qu'est-ce qu'un besoin ?)
- *Repair/*Réparer
- *Reuse/*Réutiliser les biens
- *Reduce/*Réduire la consommation
- *Refuse/*Renoncer
  « Le meilleur déchet est celui que l'on ne produit pas »
- *Recycle/*Recycler
- *Recover/*Régénérer
- *Regift/*Rallonger la phase d'usage
- [https://oldworldnew.us/circular-economy]




*Promote the shortest possible return loops*

[https://fr.wikipedia.org/wiki/économie_circulaire]

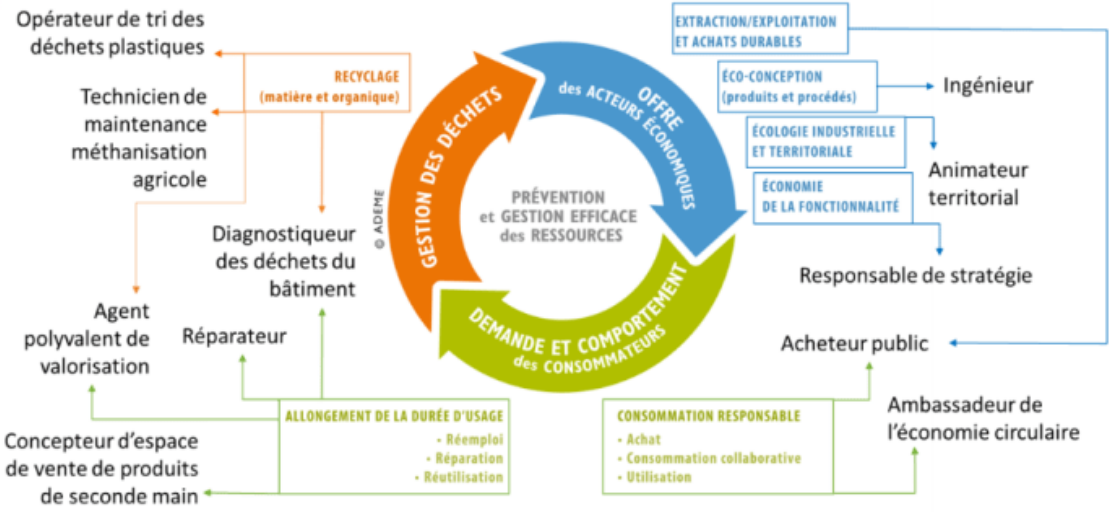
# Circular economy

The circular economy
3 areas, 7 pillars




Industrial & Territorial Ecology ⊂ circular economy

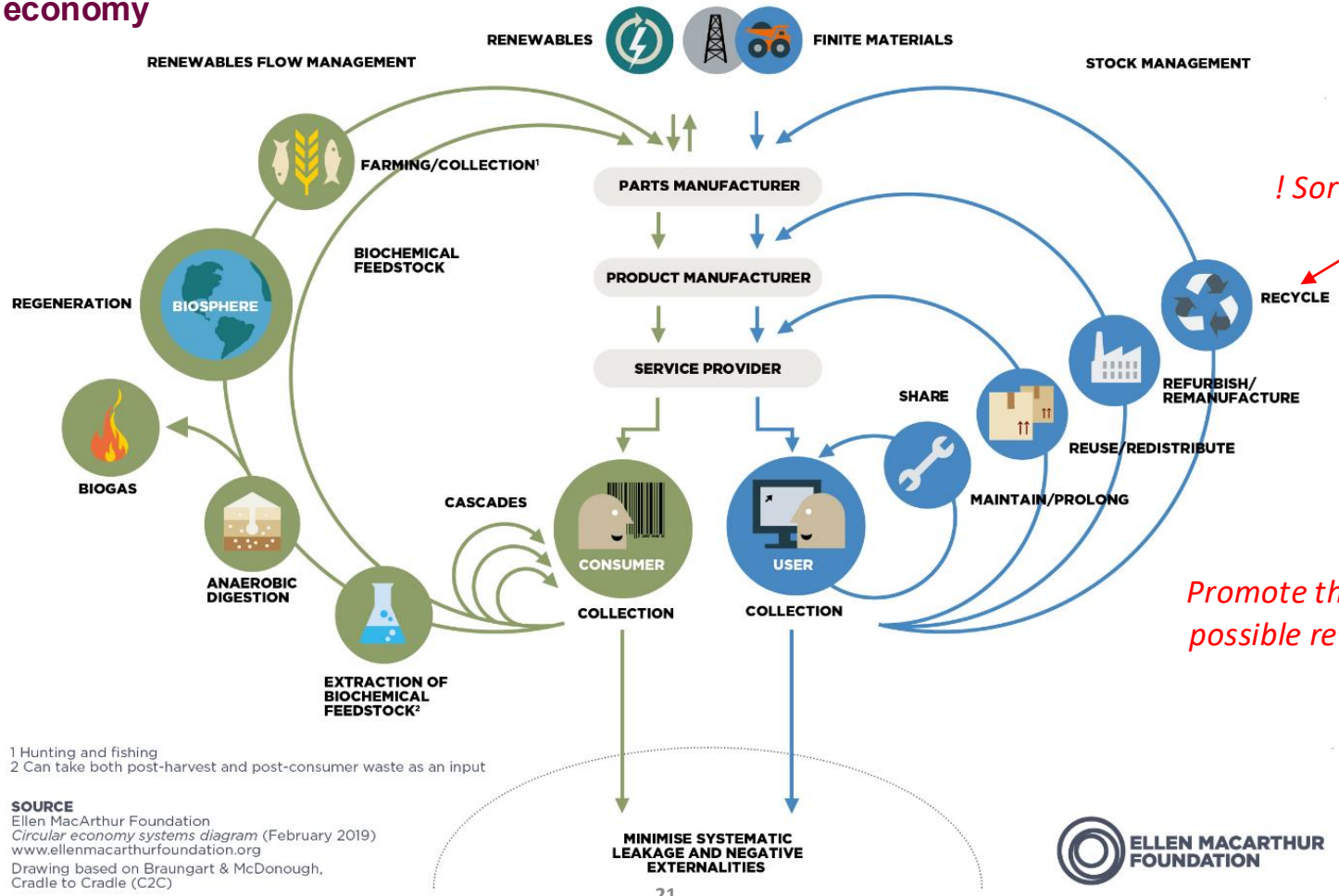
## Métiers étudiés par les GT Compétences-Formation de l'économie circulaire




*Source : ADEME et CGDD*

[Chambre Régionale de l'Economie Sociale et Solidaire Nouvelle-Aquitaine, 2019, www.cress-na.org/fiches-metier-de-leconomie-circulaire-contributions-ess]

# Circular economy




*! Sorted ≠ Recycled!*

*Promote the shortest possible return loops*



[United States Environmental Protection Agency, https://www.epa.gov/recyclingstrategy/what-circular-economy]

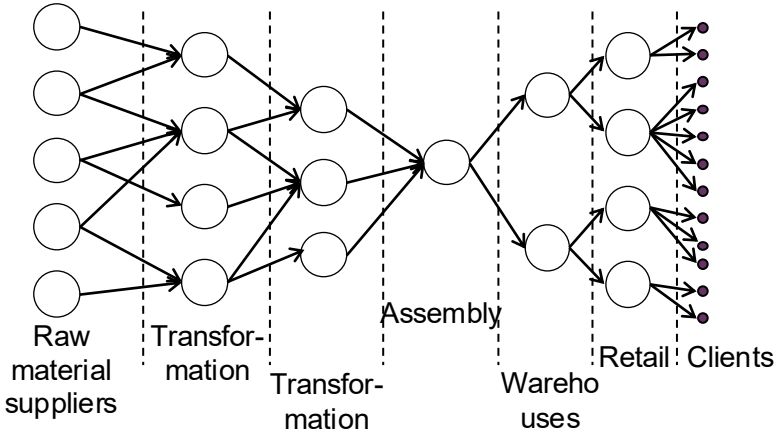
# Circular economy: Linear vs. circular economy

| Linear economy | Circular economy |
|---|---|
| Volume | Value |
| Short term | Long term |
| Competition | Cooperation |
| Always more | Sobriety |

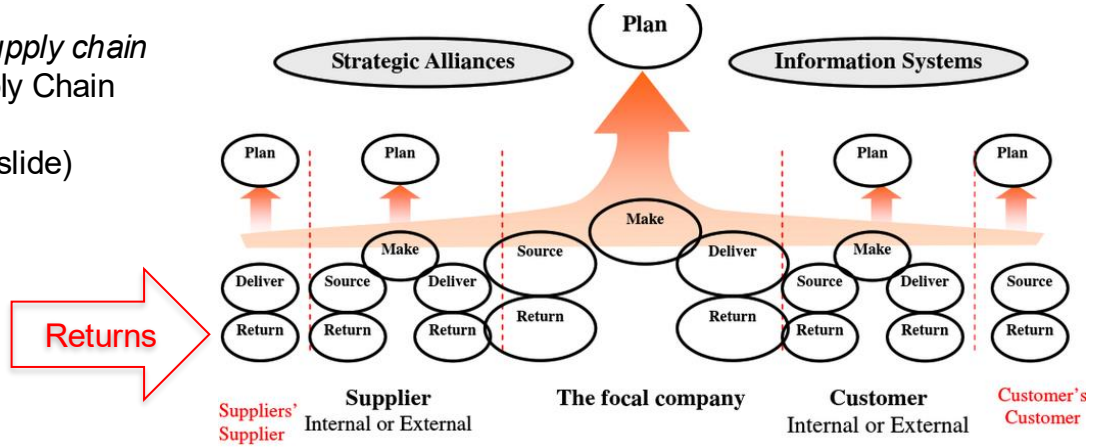
[Bortuzzo E. & Mariacher A.-F., « Fresque de l'économie circulaire », www.lafresquedeleconomiecirculaire.com]

# LCA and circular economy resemble the notion of a supply chain (1/2)

- Life cycle ≈ supply chain

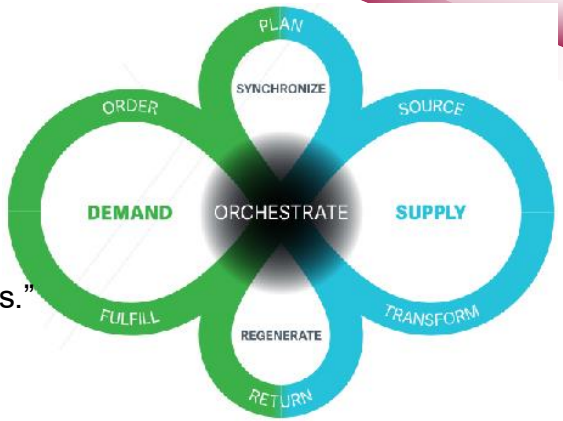



- Circular economy≈ *closed-loop supply chain*
  - Previous SCOR model: Supply Chain Operations Reference model
  - (New model on the following slide)




[W. Wang, H. Chan, D. Pauleen, Aligning business process reengineering in implementing global supply chain systems by the SCOR model Int. J. Prod. Res., 48(19):5643-5665, 2009]

# LCA and circular economy resemble the notion of a supply chain (2/2)




- Circular economy≈ *closed-loop supply chain*
  - Current SCOR model: Supply Chain Operations Reference model
    - Process
      - "A process is a unique activity performed to meet predefined outcomes."
      - Level 0 (strategic) : Only Orchestrate
        - BP.393 Circular economy
        - BP.283 Product-as-a-service
        - BP.285 Material Passport
        - BP.286 Sharing platforms
        - BP.288 Life Cycle Assessment
        - BP.289 Eco-design
        - BP.290 Material Efficiency Management
        - BP.291 Energy Efficiency Management
        - BP.292 Water Efficiency Management
        - BP.294 Sustainability reporting
        - BP.295 Emission reduction
        - BP.296 Carbon removal/offsetting
        - BP.300 Traceability
      - Level 1 : Plan, Order, Source, Transform, Fulfill, *Return*
      - Level 2 : Sous-procesus du niveau 1

[ASCM (Association for Supply Chain Management, www.ascm.org/corporate-solutions/standards-tools/scor-ds/]

# Limits of the circular economy (1/3)

The above has said that circularizing the economy is only part of the envisioned response to DDRS issues:

- Behavioural changes (individual) and/or laws and companies (collective)
- Sobriety/degrowth
- Techno-solutionism:
  - Existing : - *circular economy* (including eco-design and Industrial & Territorial Ecology)
    - Bio-sourced products
    - Planting trees
    - …
  - Hoped : - capting $CO_2$
    - nuclear fusion
    - …
- Sorted ≠ recycled
  Recyclable ≠ recycled

[recygo (co-entreprise créée par La Poste et Suez), https://www.recygo.fr/blog/dossier/papier-recycle]

# Limits of the circular economy (2/3)

Recycling myth ∞ :

- Dissipation and Entropy: « *Dissipation into the environment, contamination and wear of materials due to losses in quantity (by-products, losses of physical materials) and quality (mixing, degradation). New energies and materials must be injected into each circular material loop to overcome these dissipative losses.* » [Corvellec *et al.*, 2021, p. 3]

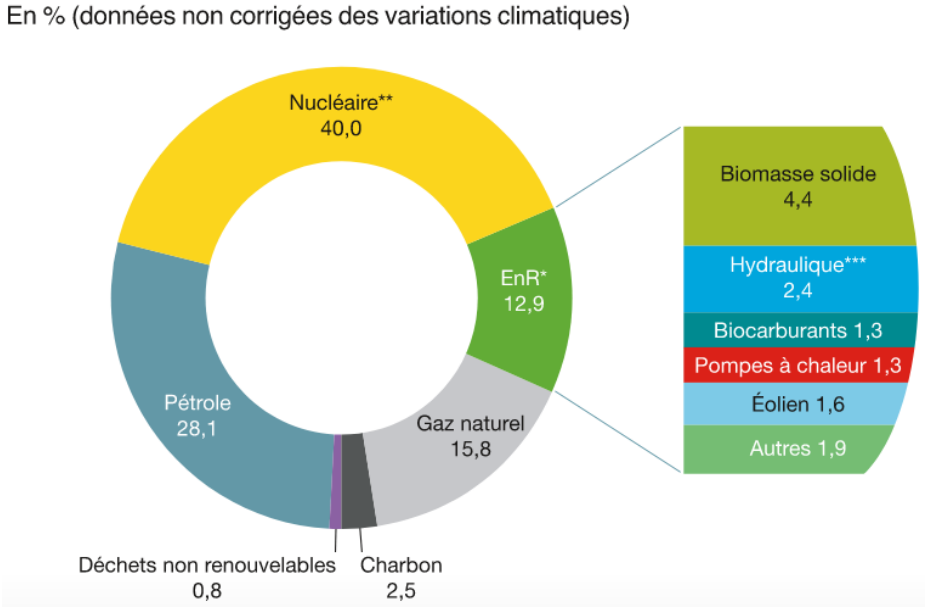
- Example: Paper recyclable 5 to 10 times because the fibres break with each recycling until they can no longer form usable paper pulp [recygo].

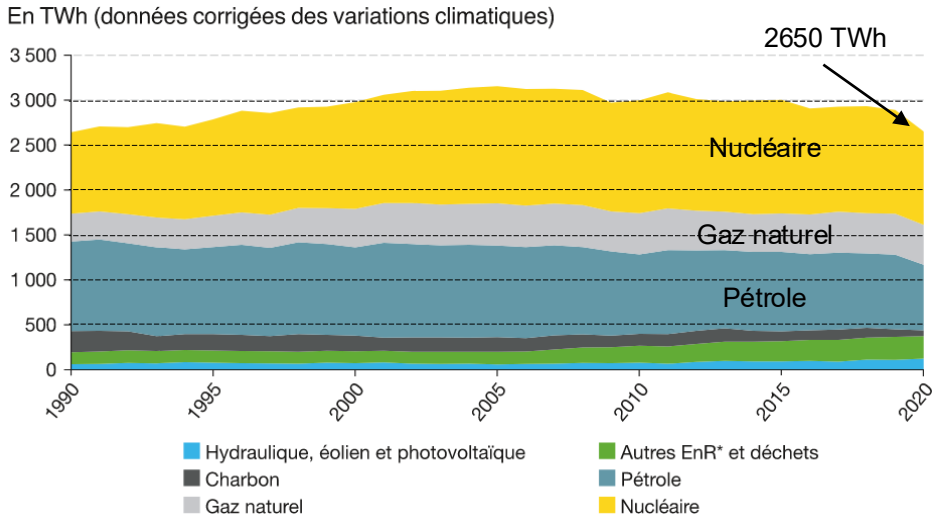
Huge energy needs: 3/4 of final energy is fossil (worldwide)

[Corvellec, H, Stowell, A. F. & Johansson, N. (2021) Critiques of the circular economy, Journal of Industrial Ecology:1-12 (revue de la littérature citant beaucoup de sources)]
[recygo (co-entreprise créée par La Poste et Suez), https://www.recygo.fr/blog/dossier/papier-recycle]

# Limits of the circular economy (3/3)

- Power requirements for the circular system to function
- France must replace or do without nearly 50% of its primary energy source:

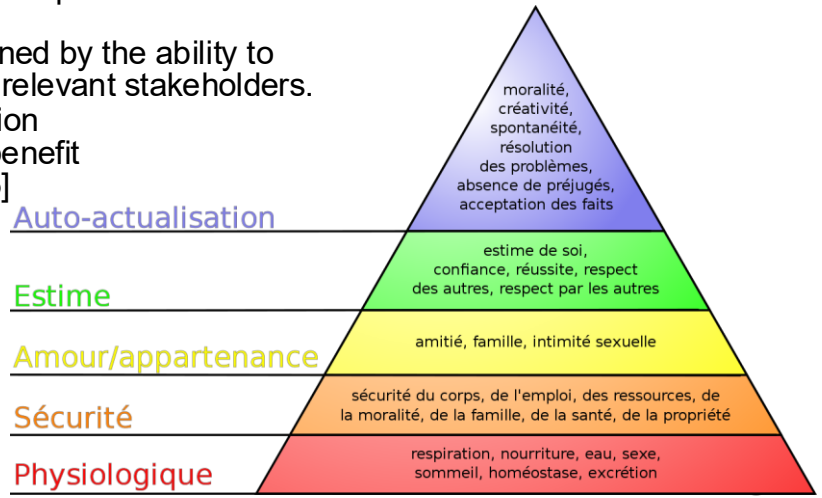



[Consommation d'énergie primaire par énergie en France https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-energie-2021/6-bilan-energetique-de-la-france]

# Definitions 1/4

- **Extension of the useful life of products** by resorting to **repair**, sale or **second-hand purchase**, by **donation**, in the context of **reuse**. [https://www.ecologie.gouv.fr/leconomie-circulaire]
- **Improving waste prevention, management and recycling**, including by reinjecting and reusing waste materials in the economic cycle. [https://www.ecologie.gouv.fr/leconomie-circulaire]
- **Sustainable sourcing**: Consider the environmental and social impacts of the resources used, especially those associated with their extraction and exploitation. [https://www.ecologie.gouv.fr/leconomie-circulaire]
- **Need, expectation and value:**
  A quality-oriented organization fosters a culture that is reflected in behaviour, attitudes, activities and processes that provide value by meeting needs and expectations customers and other relevant stakeholders.
  The quality of an organization's products and services is determined by the ability to satisfy customers and by the planned and unintended impact on relevant stakeholders.
  The quality of products and services includes not only their function and expected performance, as well as the perceived value and benefit by the customer. [Def. of qualité, parag. 2.2.1 of l'ISO 9000:2015]
- **Value**: The relationship observed or hoped for by a given actor between the satisfaction of a validated need and the resources of any kind necessary to achieve it. [NF EN 1325-2]




[https://fr.wikipedia.org/wiki/Pyramide_des_besoins]

# Definitions 2/4

- **Local short circuit**: [librairie.ademe.fr]
  - **Short circuit**: Direct sales channels or with a single intermediary between the producer and the consumer.
  - **Local circuit**: Reasonable distance between the place of production and that of consumption, varying according to the place and the products from about thirty to a hundred kilometers.
- **Collaborative consumption:** Collaborative or participatory consumption is commonly defined as the traditional way of sharing, exchanging, lending, renting and giving, reimagined in favor of modern technology and communities. [https://www.ecologie.gouv.fr/leconomie-collaborative]
- **Sustainable consumption**: Consider environmental and social impacts at all stages of the product lifecycle in purchasing choices, whether the buyer is public or private. [https://www.ecologie.gouv.fr/leconomie-circulaire]
- **Waste** : Any substance or object, or more generally any movable property, which the holder discards or intends or is obliged to dispose of. [art. L.541-1-1 du Code de l'environnement, 31/7/2020]
- **Sustainable development**: Sustainable development is a mode of development that meets the needs of present generations without compromising the ability of future generations to meet their own needs. [Rapport Bruntland, 1987]
- **Eco-design**: Take into account environmental impacts over the entire life cycle of a product and integrate them from the design stage. [https://www.ecologie.gouv.fr/leconomie-circulaire]
- **Industrial and territorial ecology**: Synergize and pool the flows of materials, energy, water, infrastructure, goods and services between several economic players in order to optimise the use of resources in a territory. [https://www.ecologie.gouv.fr/leconomie-circulaire]
- **Functional economy**: Favouring use over possession, selling a service rather than a good. [https://www.ecologie.gouv.fr/leconomie-circulaire]
- The circular economy consists of producing goods and services in a sustainable way by limiting the consumption and waste of resources and the production of waste. It is a question of moving from an all-disposable society to a more circular economic model. [https://www.ecologie.gouv.fr/leconomie-circulaire, 2020]

# Definitions 3/4

- **Reuse (Réemploi):** Any operation by which substances, materials or products that are not waste are reused for a purpose identical to that for which they were designed [art. L.541-1-1 du Code de l'environnement, 31/7/2020]

- **Reuse (Réutilisation)**: Any operation by which substances, materials or products that have become waste are reused [art. L.541-1-1 du Code de l'environnement, 31/7/2020]

- **Refurbishment:** A second-hand product or spare part may be qualified as a "refurbished product" if the following conditions are met: (1) The product or spare part has undergone tests covering all its functionalities in order to establish that it meets the legal obligations of safety and the use that the consumer can legitimately expect; (2) If necessary, the product or spare part has undergone one or more interventions in order to restore its functionality. This includes the deletion of all data recorded or retained in connection with a previous use or user, before the product or part changes ownership. [Art. R. 122-4.- Décret n° 2022-190 du 17 février 2022]

- **Remanufacturing**: A rigorous and standardized process for restoring a used part or product to a state of performance and functionality equivalent to or even better than that of the original and for the same use, differs from reconditioning by the fact that it results in the refurbishment of used components or products with a uniform quality grade and performance. Remanufacturing is the most comprehensive value retention process […] [https://librairie.ademe.fr/dechets-economie-circulaire/6249-etude-sur-la-remanufacture.html]

- **Recycling** : Any recovery operation by which waste, including organic waste, is reprocessed into substances, materials or products for their original function or for other purposes. Waste-to-energy operations, waste-to-fuel operations and backfilling operations cannot be classified as recycling operations [art. L.541-1-1 du Code de l'environnement, 31/7/2020]

# Définitions 4/4

- **Responsabilité Elargie des Producteurs (REP)** : REP channels are specific arrangements for organising waste prevention and management, which concern certain types of products. They are based on the principle of extended producer responsibility, recognised in the EU Waste Framework Directive, according to which the persons responsible for placing products on the market can be made responsible for ensuring the prevention and management of waste from these products at the end of their life.
  This is an application of the polluter-pays principle.
  [https://www.ecologie.gouv.fr/cadre-general-des-filieres-responsabilite-elargie-des-producteurs]
- **Retrofit** : The process of replacing old or obsolete components with newer ones, usually by changing the technology, without changing the function. [https://fr.wiktionary.org/wiki/rétrofit]
- **Synergy** : *Multi-stakeholder action that aims to increase resource efficiency*
  either in a "substitution" logic (where the residual material of one company can be used by another),
  or in a logic of « pooling ». The implementation of these synergies makes it possible to optimise the management of tangible or intangible resources at the scale of a territory (business park, community of municipalities, department, etc.):
  - *Substitution* synergies: the exchange and recovery of materials and energy between several companies: heat, steam, industrial water, waste, packaging, and co-products…
  - *Synergies in the pooling of resources and services*: … group purchasing, common logistics, collective waste management, inter-company restaurant, nursery, company concierge service, security, fire systems, etc., but also the sharing of equipment or resources: heating/cooling network, WWTP, boiler room, anaerobic digestion unit, car park, meeting place, time-sharing jobs, shared audits
    [Club d'Ecologie Industrielle de l'Aube, www.ceiaube.fr/presentation-ecologie-industrielle]

# Today

1. Overview of the 14 sessions
2. Context
3. Definitions
4. *Exercises*

## Exercise 1: Place the following terms on the figure of the next slide

Industrial & Territorial Ecology (synergies)

REP

Responsible consumption/zero waste

Collaborative consumption

Sustainable Sourcing

Eco-design

Réutilisation

Reuse

Renovation/retrofit

Repair

Functional economy

Local short circuit

Recycling

Refurbushing

Upgrade

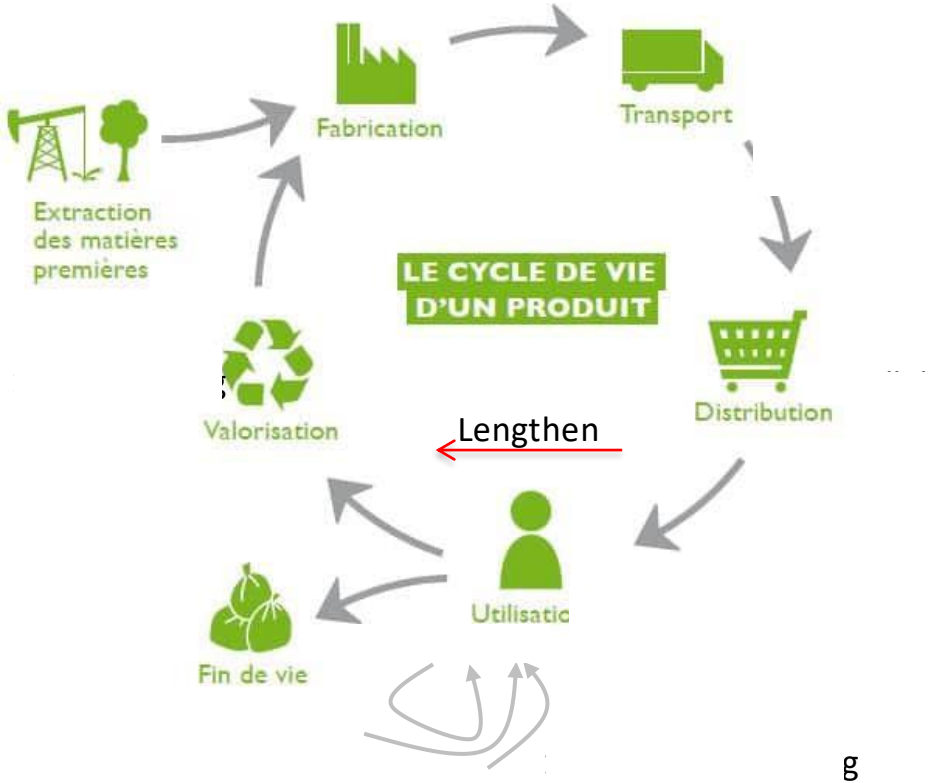
[Image de https://presse.ademe.fr/2016/03/avis-allongement-de-la-duree-de-vie-des-produits.html], [Exercice inspiré de Bortuzzo E. & Mariacher A.-F., « Fresque de l'économie circulaire », www.lafresquedeleconomiecirculaire.com]

# Exercise 1: Figure to be filled in




[Image de https://presse.ademe.fr/2016/03/avis-allongement-de-la-duree-de-vie-des-produits.html], [Exercice inspiré de Bortuzzo E. & Mariacher A.-F., « Fresque de l'économie circulaire », www.lafresquedeleconomiecirculaire.com]

# Exercise 1: A possible solution (what is hidden is on Moodle)




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[Image de https://presse.ademe.fr/2016/03/avis-allongement-de-la-duree-de-vie-des-produits.html], [Exercice inspiré de Bortuzzo E. & Mariacher A.-F., « Fresque de l'économie circulaire », www.lafresquedeleconomiecirculaire.com]

# Exercise 2: Name a concept seen above and propose a company that implements it

- **Short Circuit** : www.camif.fr (vente par correspondance de 77% de made in France et 100% made in Europe)
- **Retrofit** : www.renaultgroup.com/groupe/implantations/usine-flins
- ..... : https://velov.grandlyon.com + https://citiz.coop
- ..... : carpool (www.blablacar.com...) + Pooling of storage spaces between companies (www.spacefill.eu) + Physical Internet
- ..... : lesbiensencommun.com
- ..... : www.adopteunbureau.fr
- ..... : www.backmarket.fr
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# Conclusion

Give (anonymously) a piece of paper with a strong idea that you remember from this session