Biofuels Assessing Technology Readiness Levels and Investment Risk

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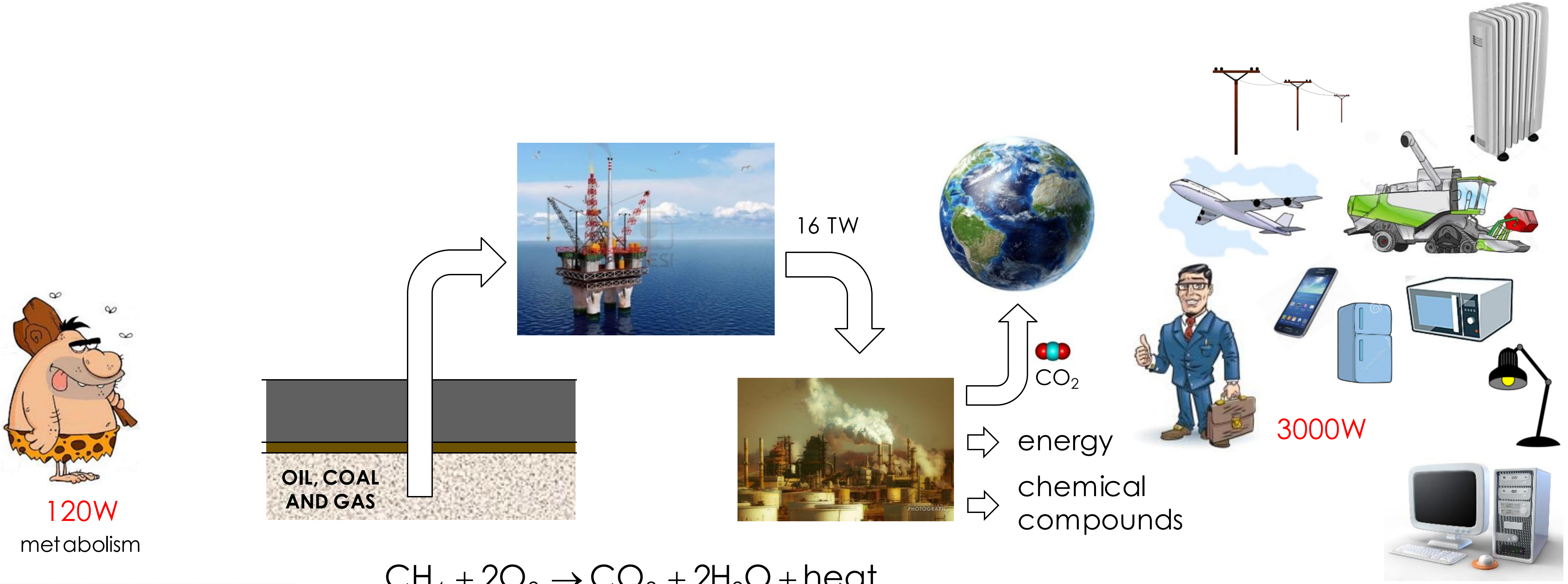
conversion route for biomass feedstocks...

THE PROBLEM

RENEWABLE ENERGIES COMPETE WITH FOSSIL ONES:

economical and technical aspects (drop in)

Fossil carbon based economy...



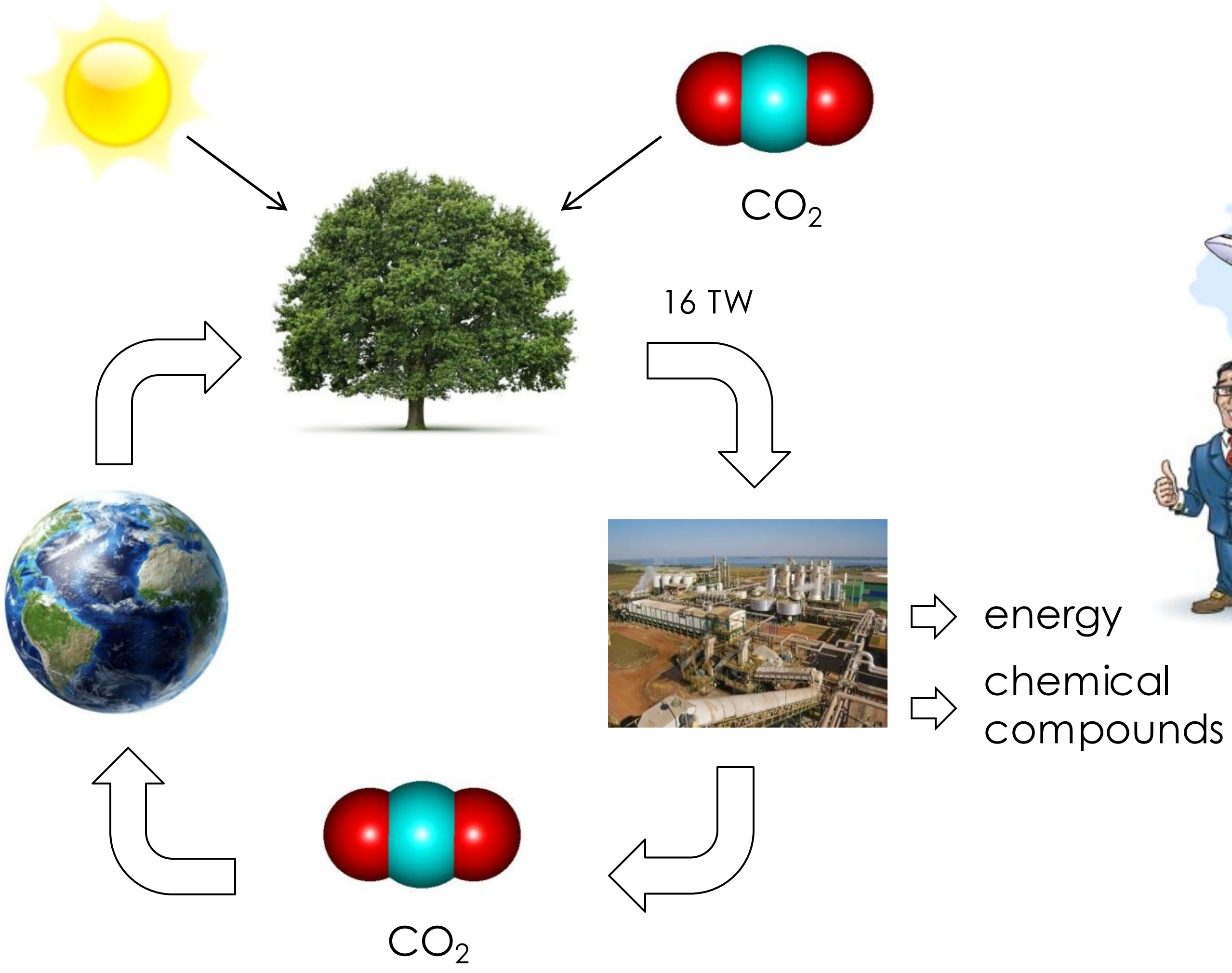
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + heat$$

$$\Downarrow \ \eta_{carnot}$$

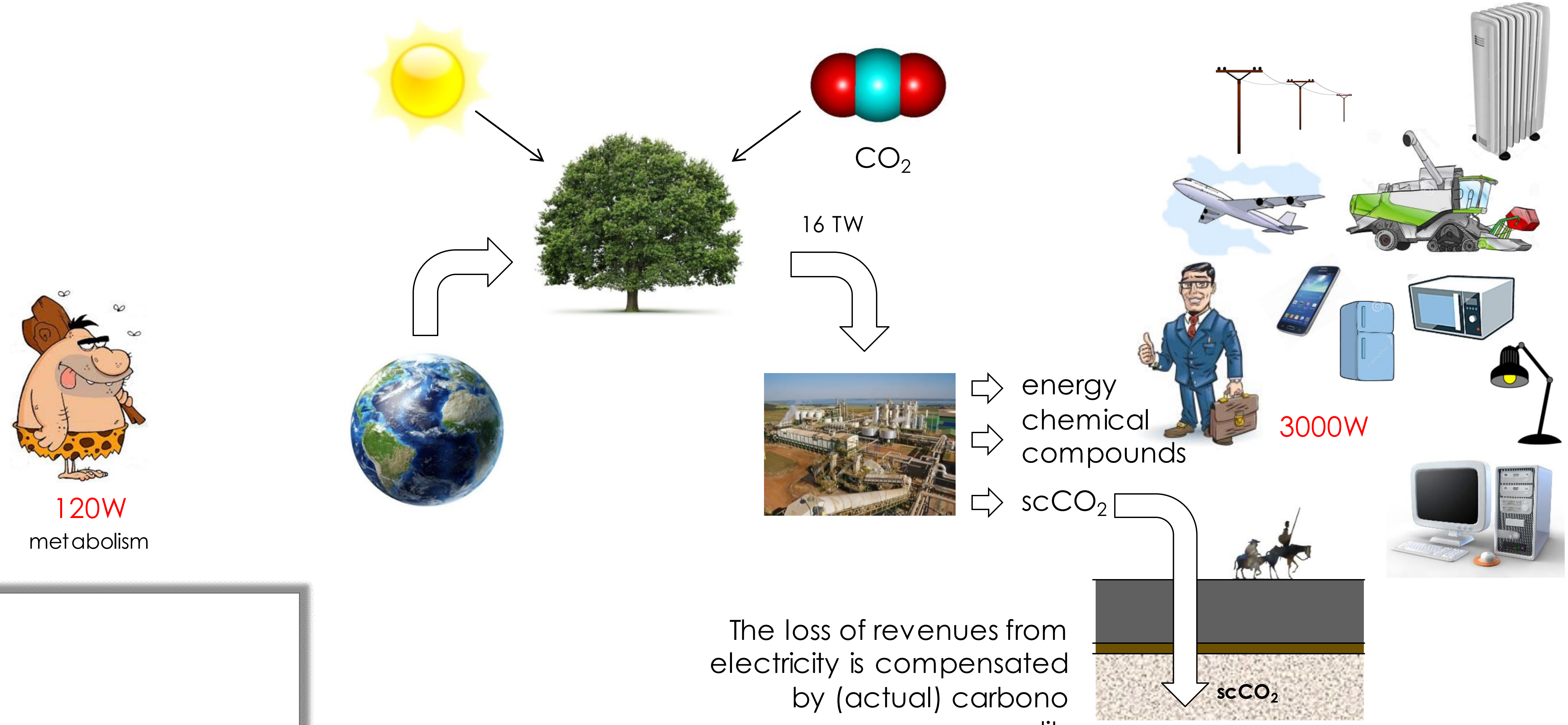
exergy

Renewable carbon based economy... (neutral)

120W
metabolism

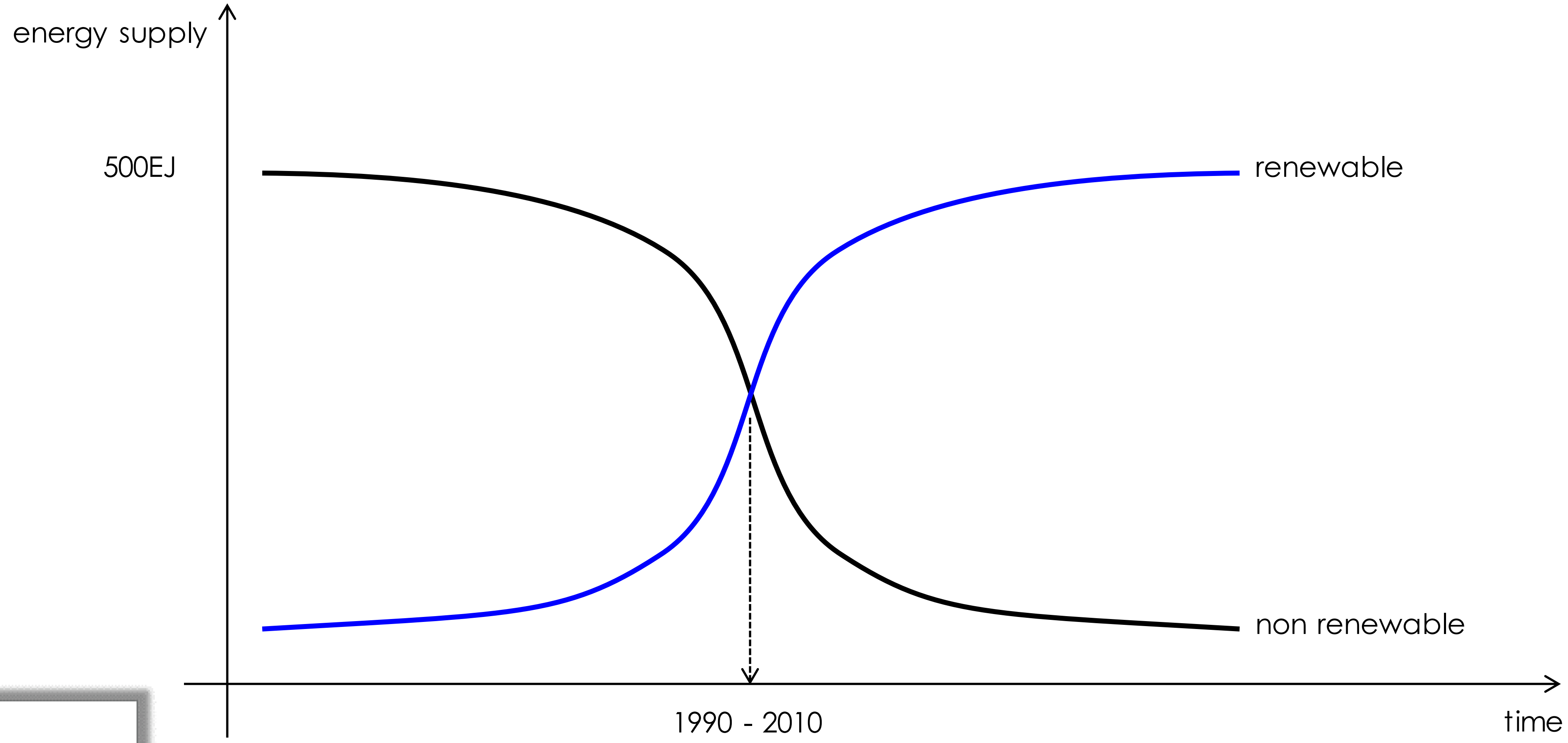


Renewable carbon based economy... (negative)

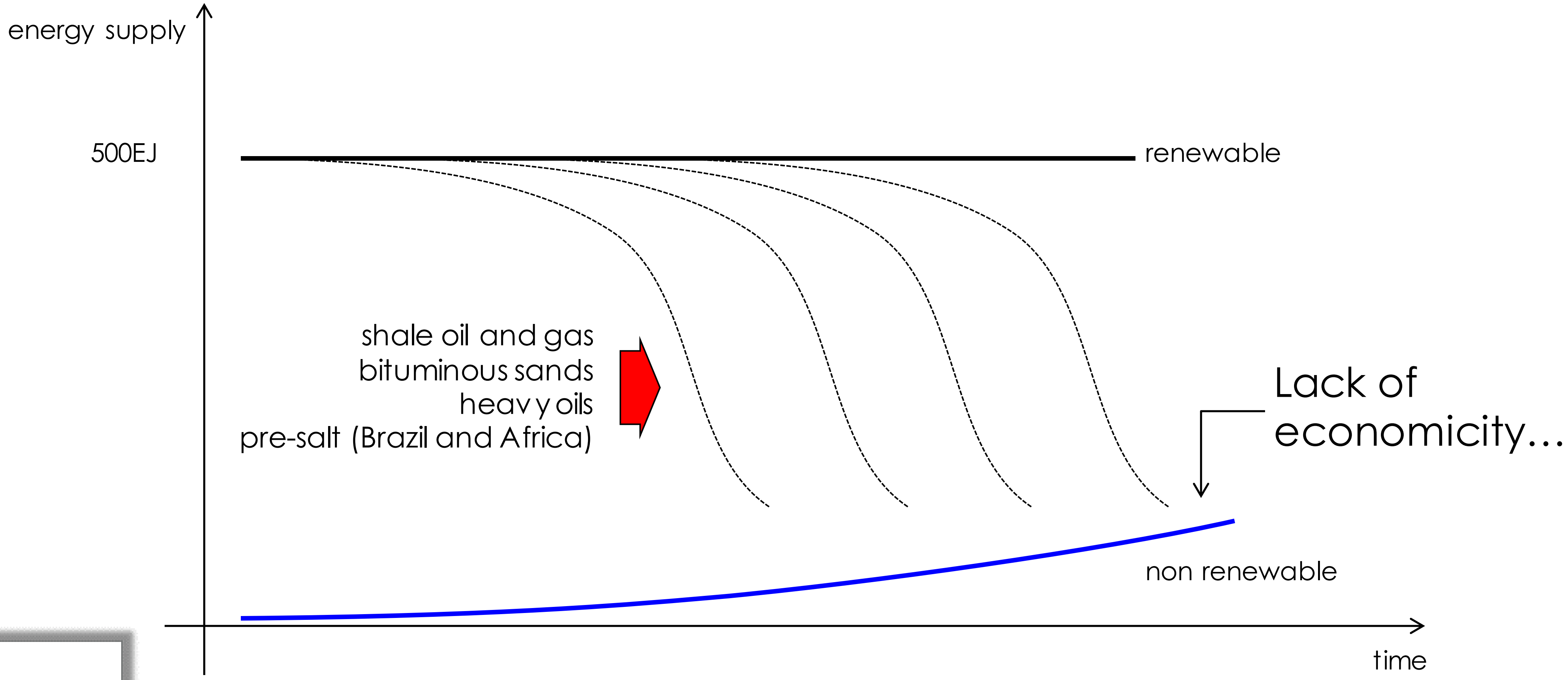


The loss of revenues from electricity is compensated by (actual) carbono credits

Displacement of fossil by renewable fuels: the Hubert Law

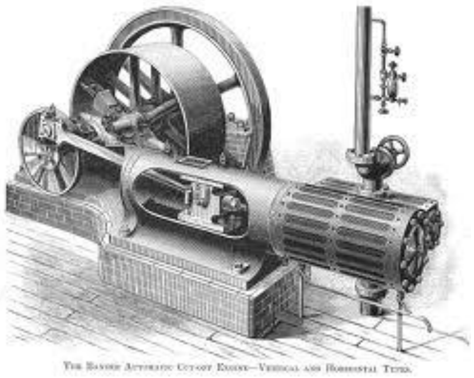


Displacement of fossil by renewable fuels: the Hubert Law



Accumulated experience in the use of fossil energy resources…

coal

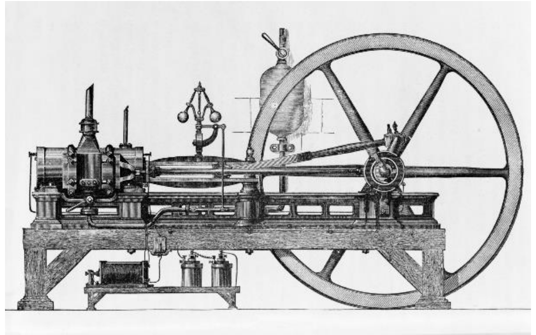


Steam engine
since ~1800

200 years !

James Watt,
1736–1819

petroleum fuel



IC engine
since ~1900

100 years !

Nikolaus Otto
1832-1891

Rudolf Diesel
1858 – 1913

THE PROBLEM WITHIN THE PROBLEM:

biomass conversion technologies must be competitive **enough** to displace fossil fuels

… but how much is enough ?

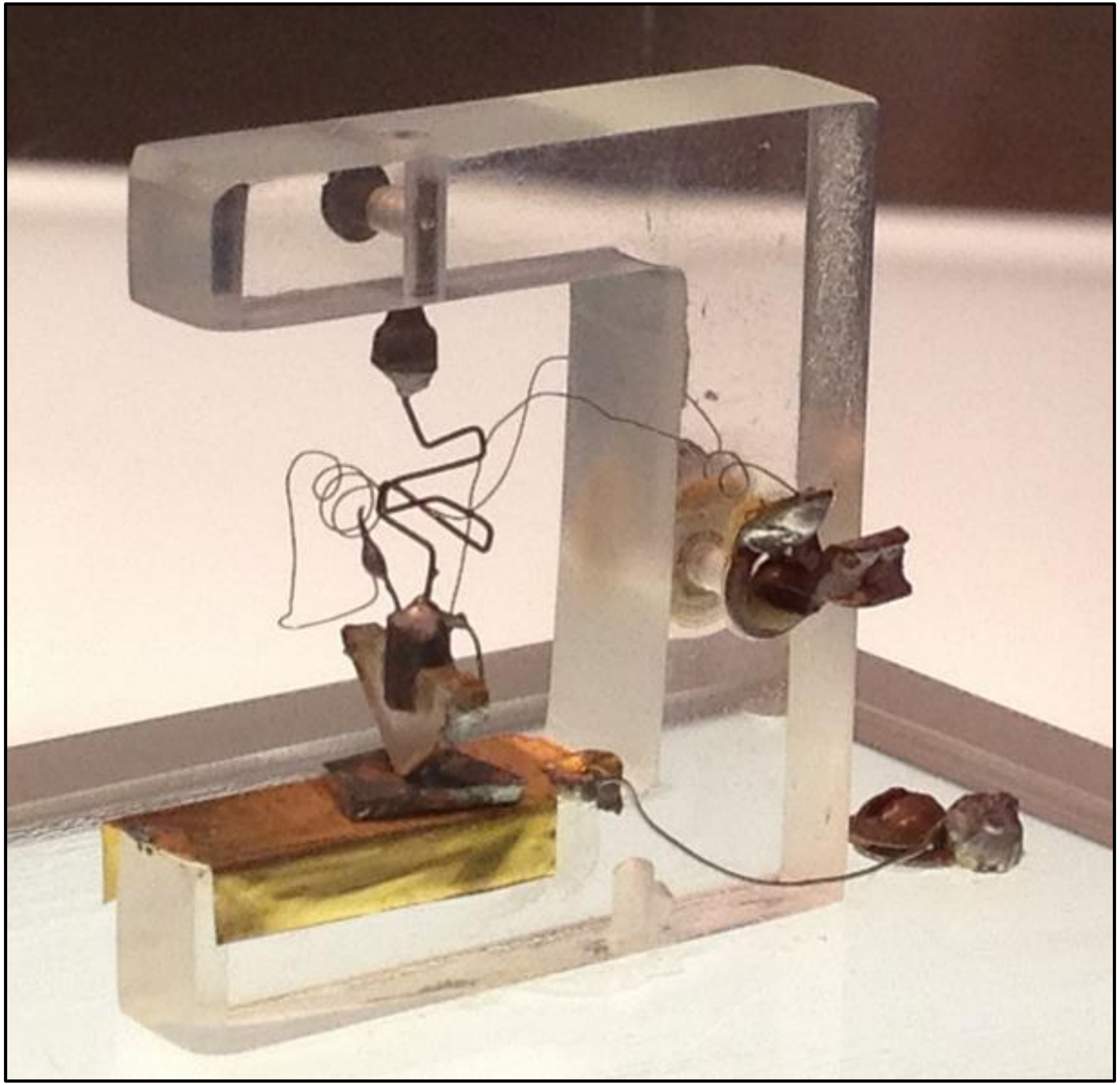
Technology assessment:

- Technology readiness levels (TRLs)
- Brief history and definitions
- Assessment tools
- Technology deployment: risk management and decision making

Technology readiness levels (TRLs)

- A measure of the **maturity of an evolving technology** relative to its development cycle
- Identifying the **critical technology elements** and developing a **technology maturation plan**
- Support decision making by providing a **reference framework** for understanding of technology status to facilitate **risk management**, attract external funding, etc.

How much would you invest in this idea (1947) ?



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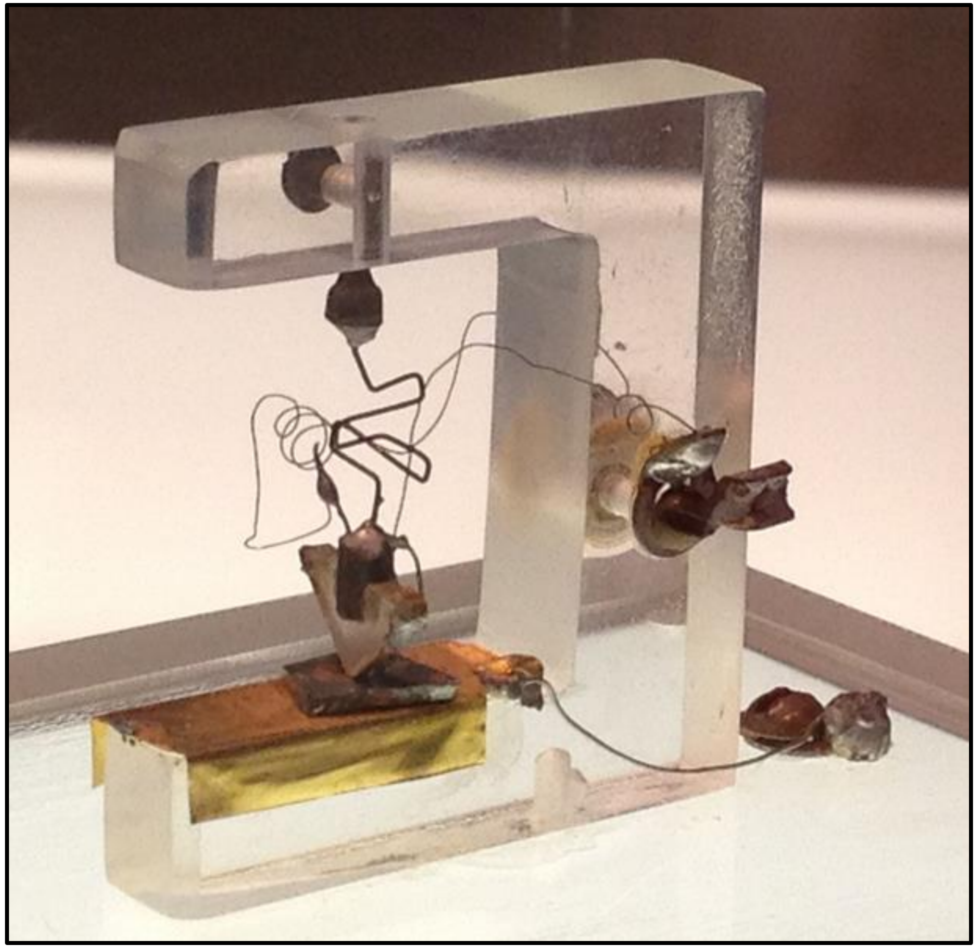
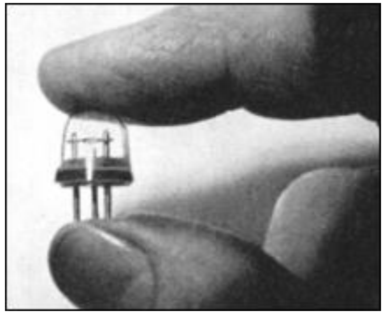
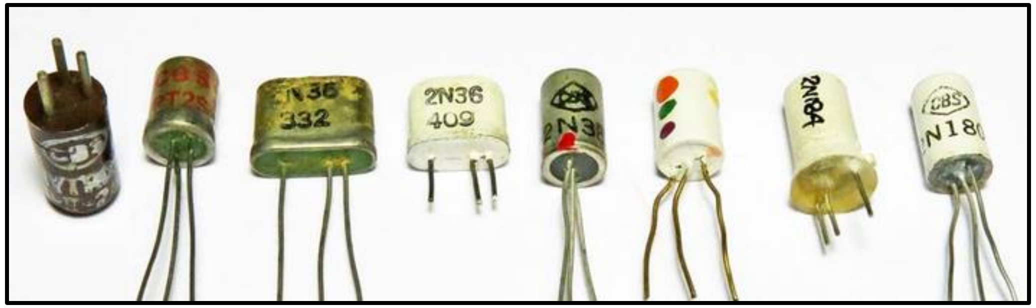
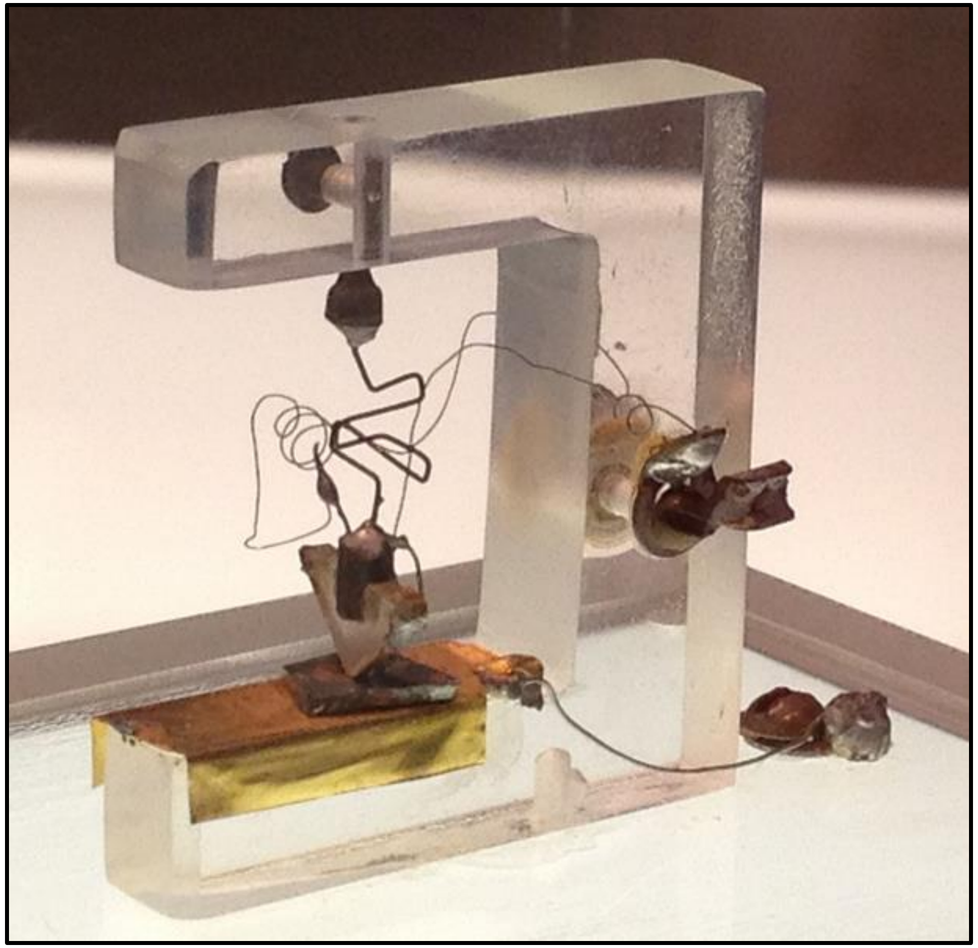








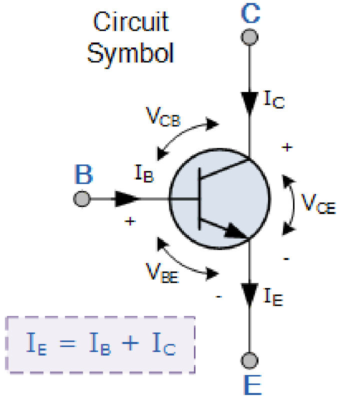
How much would you invest in this idea (1947) ?

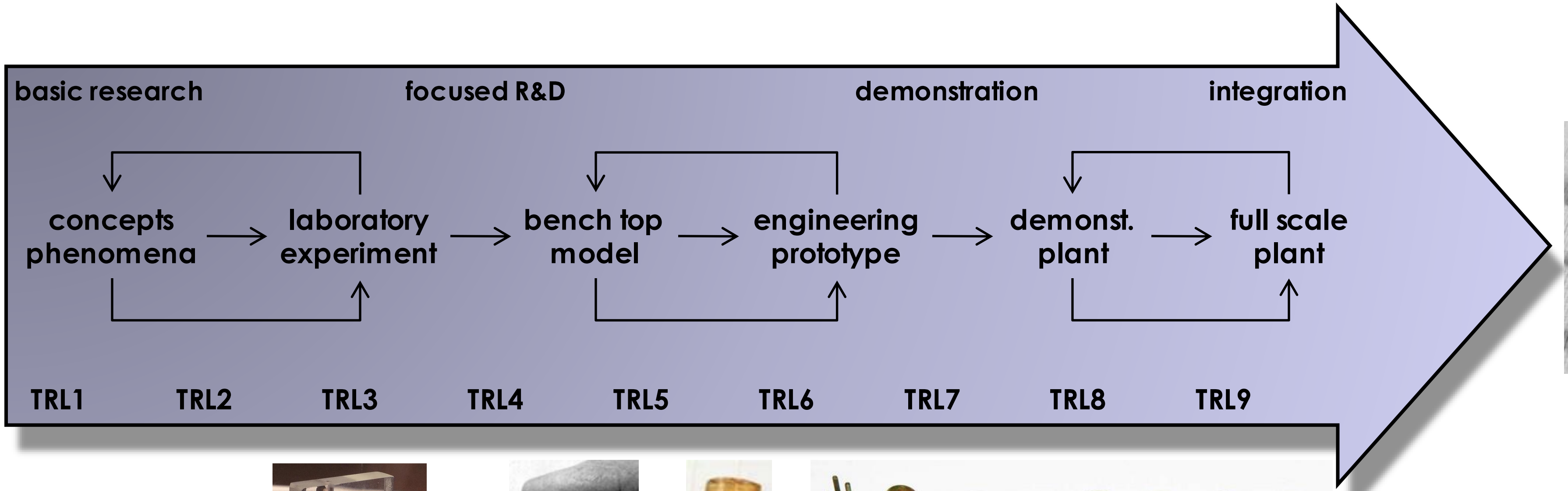
40 years

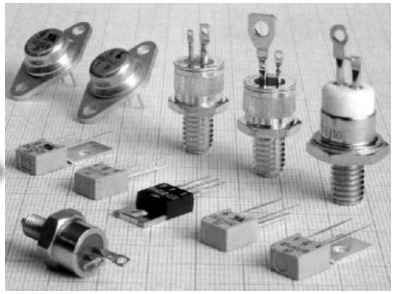
miniaturization
integration

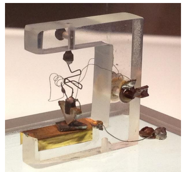
In 2015, global sales exceeded 335 billion U.S. dollars…

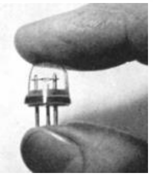
Technology readiness levels (TRLs)



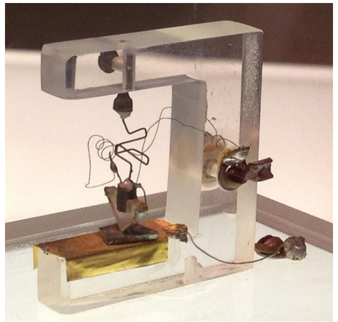




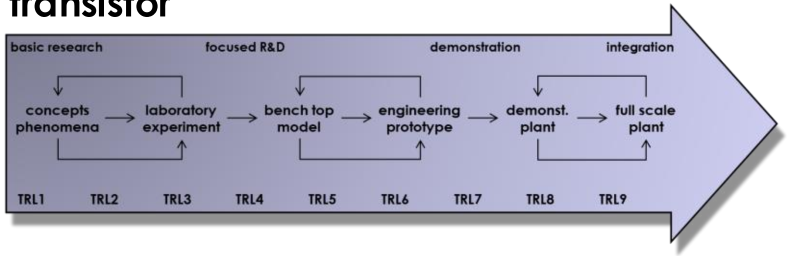




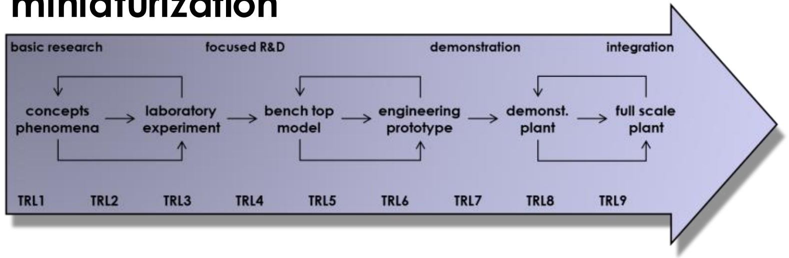
Technology readiness levels (TRLs): synergic technologies



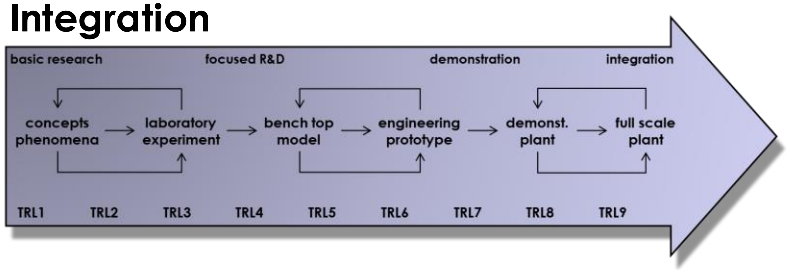
transistor



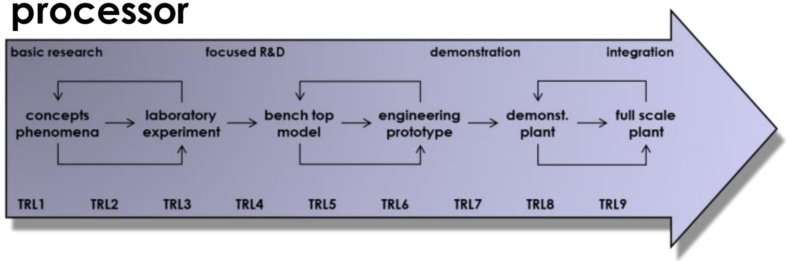
miniaturization

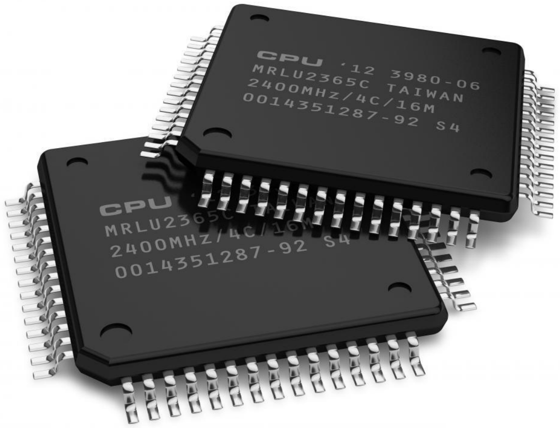


Integration

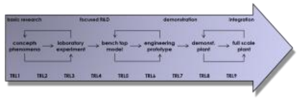


processor





Thomas Newcomen's "engine for raising water by fire"



1 GW Thermal Power Plant

Technology readiness levels definitions…

- NASA definitions
- European Space Agency (ESA)
- U.S. Department of Defense
- Oil & Gas Industry (API 17N)
- European Commission (EC)
- U.S. Department of Energy

Conceptually similar, differences arise to cope with specificities of the area…

U.S. Department of Energy TRL’s

TRL1 Basic principles observed and reported

Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.

TRL2 Technology concept and/or application formulated

Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.

U.S. Department of Energy TRL's

TRL3 Analytical and experimental critical function and/or characteristic proof of concept

Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

TRL4 Component and/or pilot validation in laboratory environment

Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.

U.S. Department of Energy TRL's

TRL5 Component and/or pilot validation in relevant environment

Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.

TRL6 System/subsystem model or prototype demonstration in a relevant environment

Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.

U.S. Department of Energy TRL's

TRL7 System prototype demonstration in an operational environment.

Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).

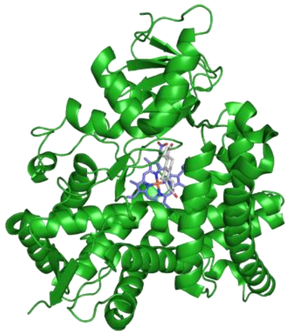
TRL8 Actual system completed and qualified through test and demonstration.

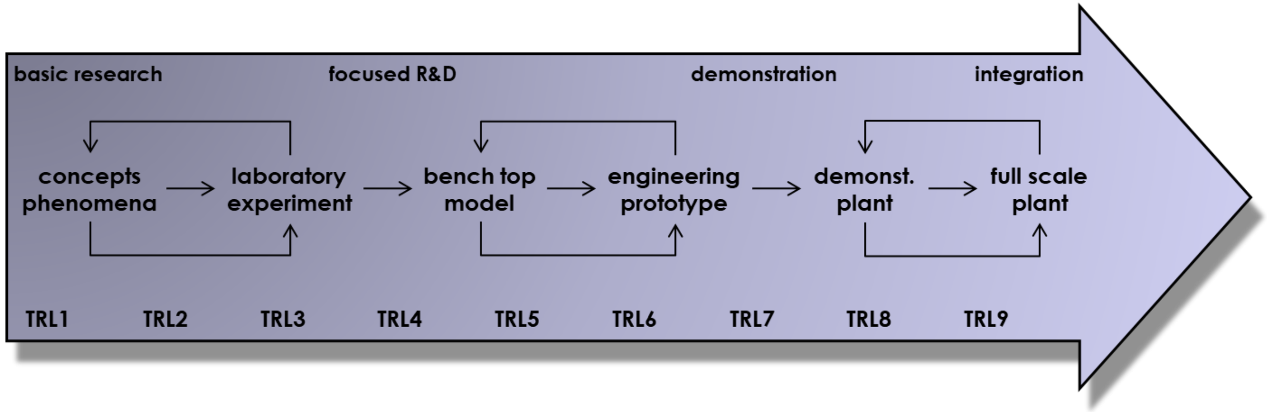
Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended application to determine if it meets design specifications.

U.S. Department of Energy TRL's

TRL9 Actual system proven through successful mission operations.

Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.





Industrial Production of Biofuels:

Learning through Experience

Technology readiness assessment tools

Basic guideline: a consistent and reproducible method of assigning a TRL to a specific technology based on surveys and polls… → **questionnaires**

	Overall Evaluation ↓	TRL specific ↓
Yes/no answers (0/1)→		
Quantitative (0-100%)→		

Technology readiness assessment tools

Basic guideline: a consistent and reproducible method of assigning a TRL to a specific technology based on surveys and polls… → **questionnaires**

Overall Evaluation ↓

TRL specific ↓

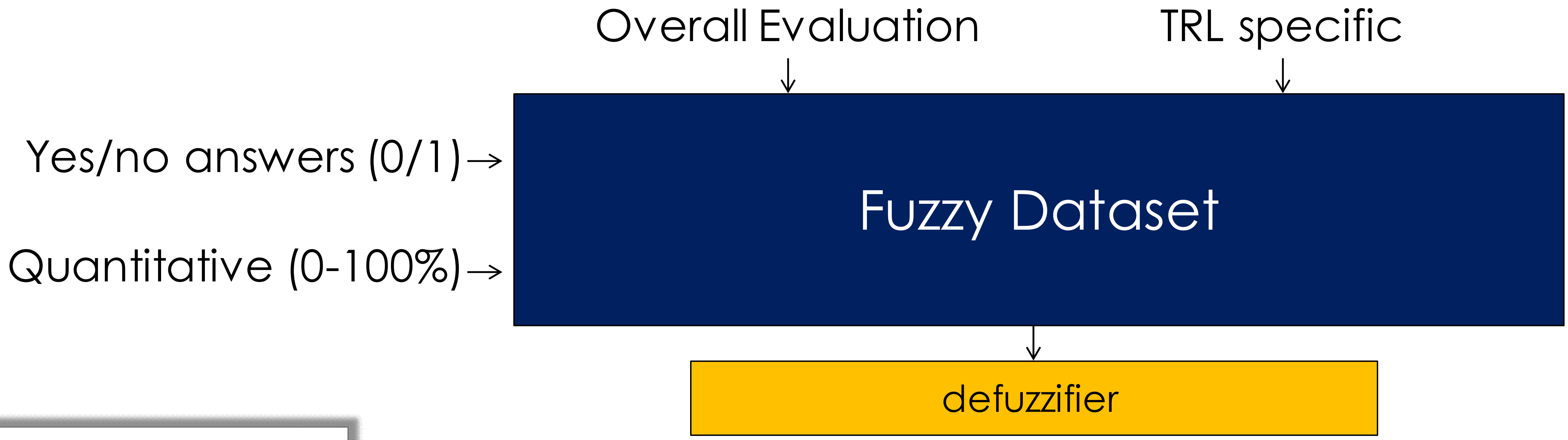
Yes/no answers (0/1) →

Quantitative (0-100%) →

Fuzzy Dataset

Technology readiness assessment tools

Basic guideline: a consistent and reproducible method of assigning a TRL to a specific technology based on surveys and polls… → **questionnaires**



Technology readiness assessment tools

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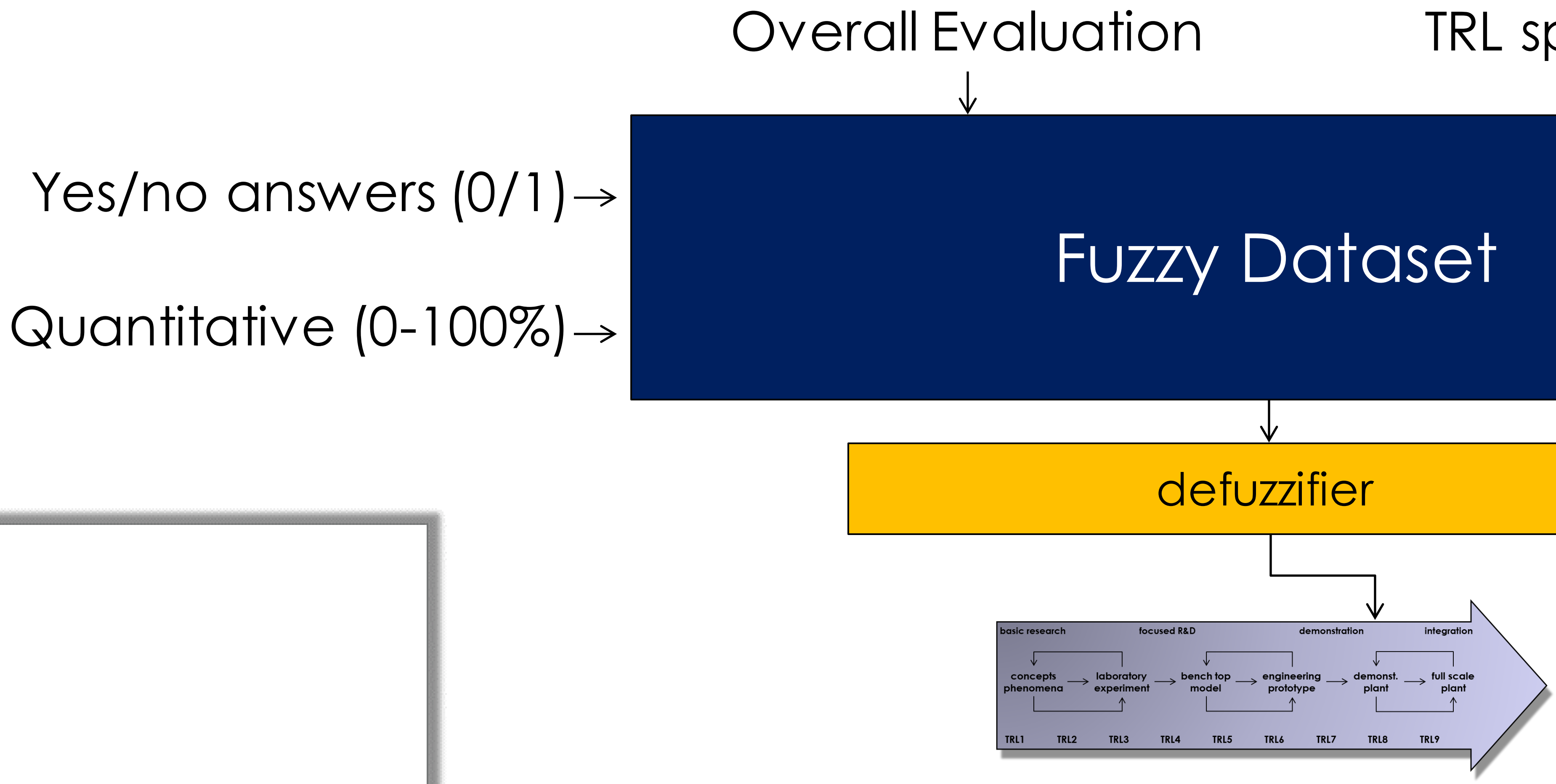


Example of questions related to an overall evaluation...

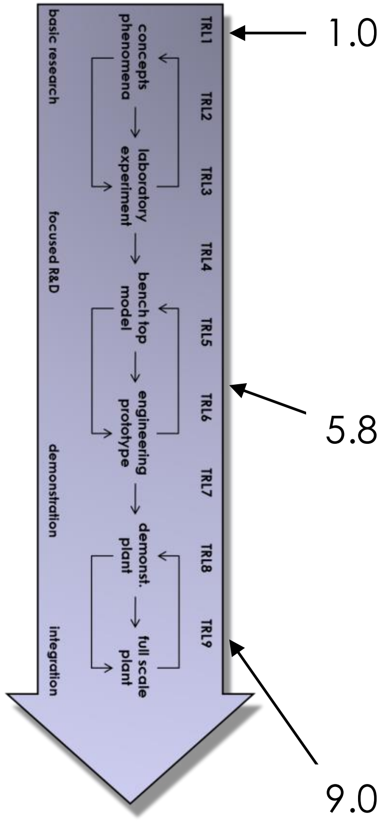
Less Mature

More Mature

2nd generation ethanol pilot plant

- Have basic principles been observed and reported ?
- Has a concept or application been formulated ?
- Has analytical and experimental proof-of-concept been demonstrated ?
- Has a pilot unit been demonstrated in a laboratory (controlled) environment ?
- Has a pilot unit been demonstrated in a relevant environment ?
- Has a prototype unit been demonstrated in the operational environment ?
- Has an identical unit been qualified but not operationally demonstrated ?
- Has an identical unit been demonstrated on an operational application, but in a different configuration/system architecture ?
- Has an identical unit been successful an on operational in an identical configuration ?

Example of questions related to an overall evaluation…

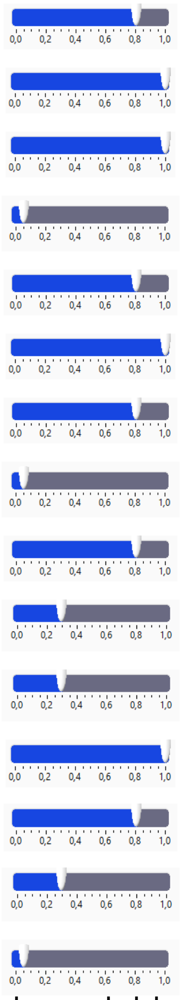


- ✓ Have basic principles been observed and reported ?
- ✓ Has a concept or application been formulated ?
- ✓ Has analytical and experimental proof-of-concept been demonstrated ?
- ✓ Has a pilot unit been demonstrated in a laboratory (controlled) environment ?
- ✓ Has a pilot unit been demonstrated in a relevant environment ?
- ✗ Has a prototype unit been demonstrated in the operational environment ?
- ✗ Has an identical unit been qualified but not operationally demonstrated ?
- ✗ Has an identical unit been demonstrated on an operational application, but in a different configuration/system architecture ?
- ✗ Has an identical unit been successful an on operational in an identical configuration ?

Example of questions related to TRL specific evaluation…

TRL7 System prototype demonstration in an operational environment

2nd generation ethanol pilot plant

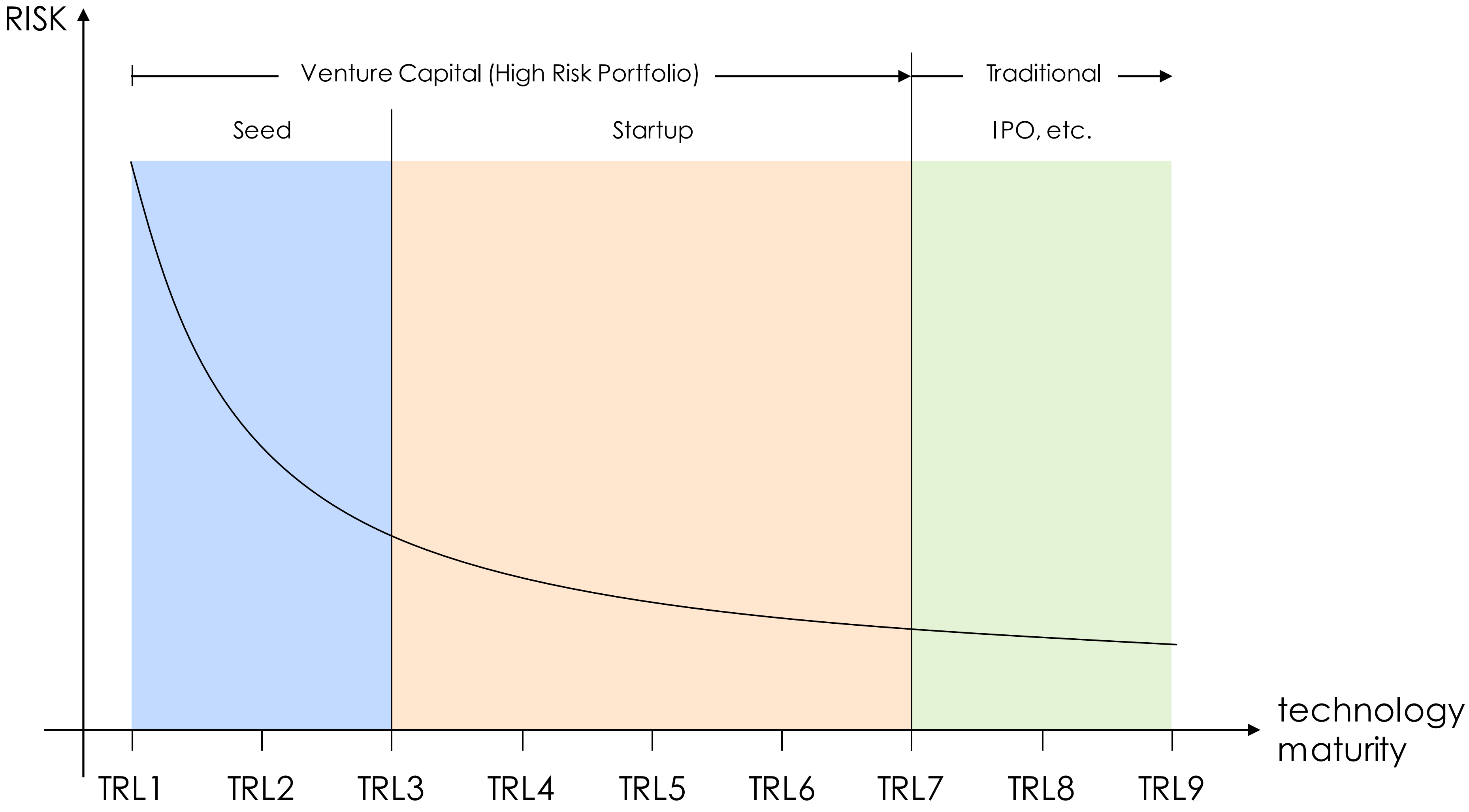


- Materials, processes, methods, and design techniques have been identified
- Each system/subsystem tested individually under stressed and anomalous conditions
- Systems/subsystems run in operating environment
- Process tooling and inspection / test equipment demonstrated in production environment
- Design changes decrease significantly
- Operational environment, but not the eventual platform, e.g., test-bed aircraft
- Draft design drawings are complete
- Scaling is complete
- Operation processes generally well understood
- Operation planning is complete
- Most functionality available for demonstration in simulated operational environment
- Operational testing of laboratory system in representational environment
- Fully integrated pilot demonstrated in actual or simulated operational environment
- System pilot successfully tested in a field environment
- Ready for Low Rate Initial Operation (LRIO)

defuzzifier
(clever mathematical formulas)

→ TRL = 6.6

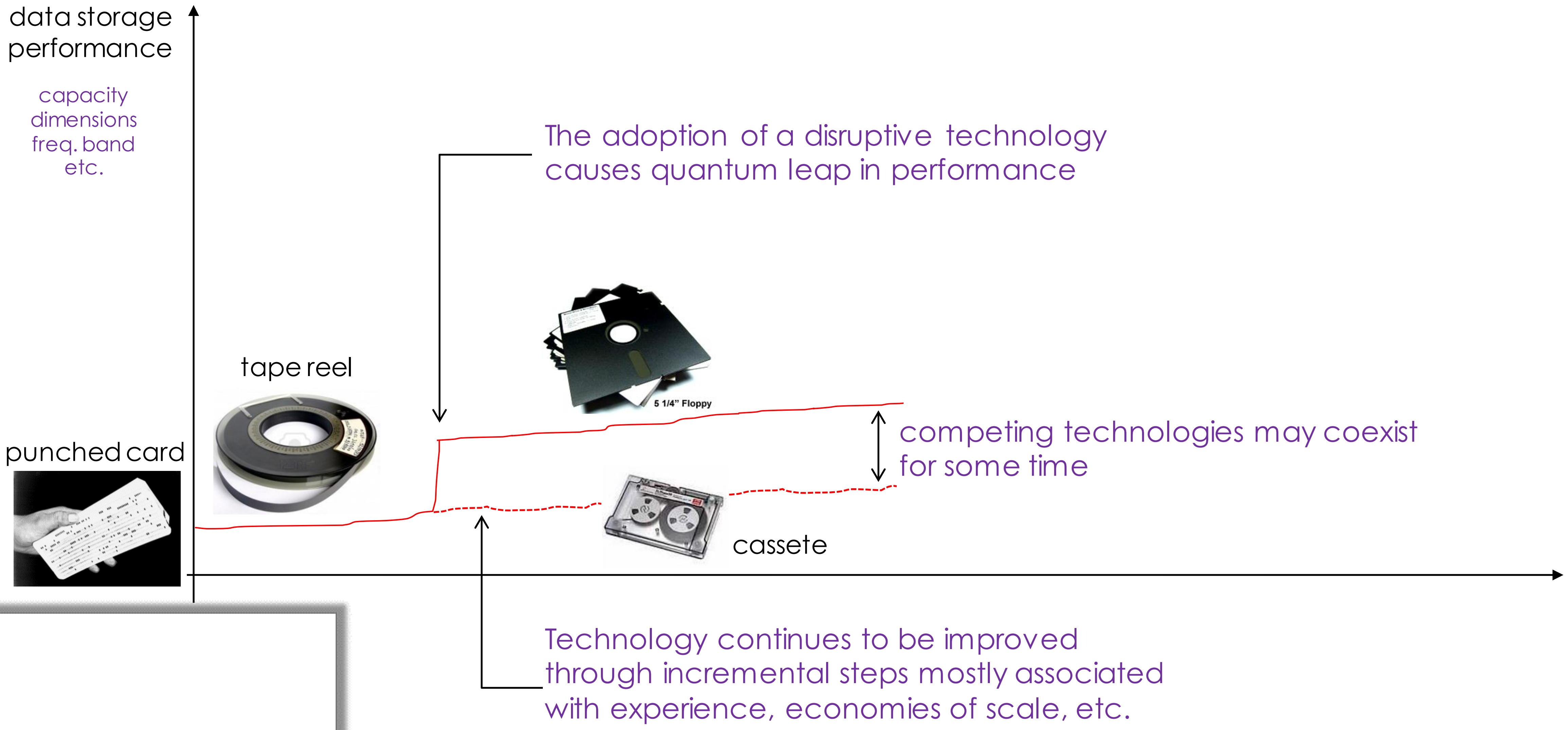
TRL based risk management and decision making



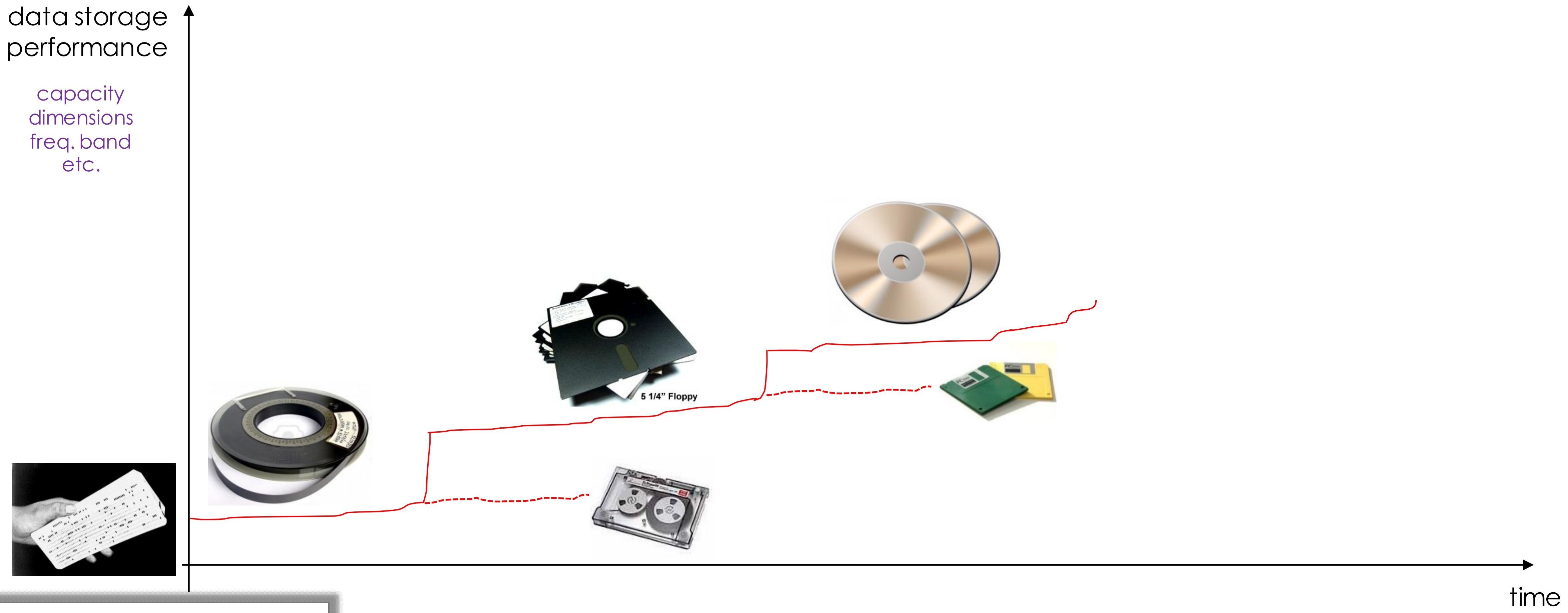
Technology evolution: incremental × disruptive

- Innovation and technological transitioning
- Technology diffusion and the learning curve
- Social impacts – driving and regulating technological change

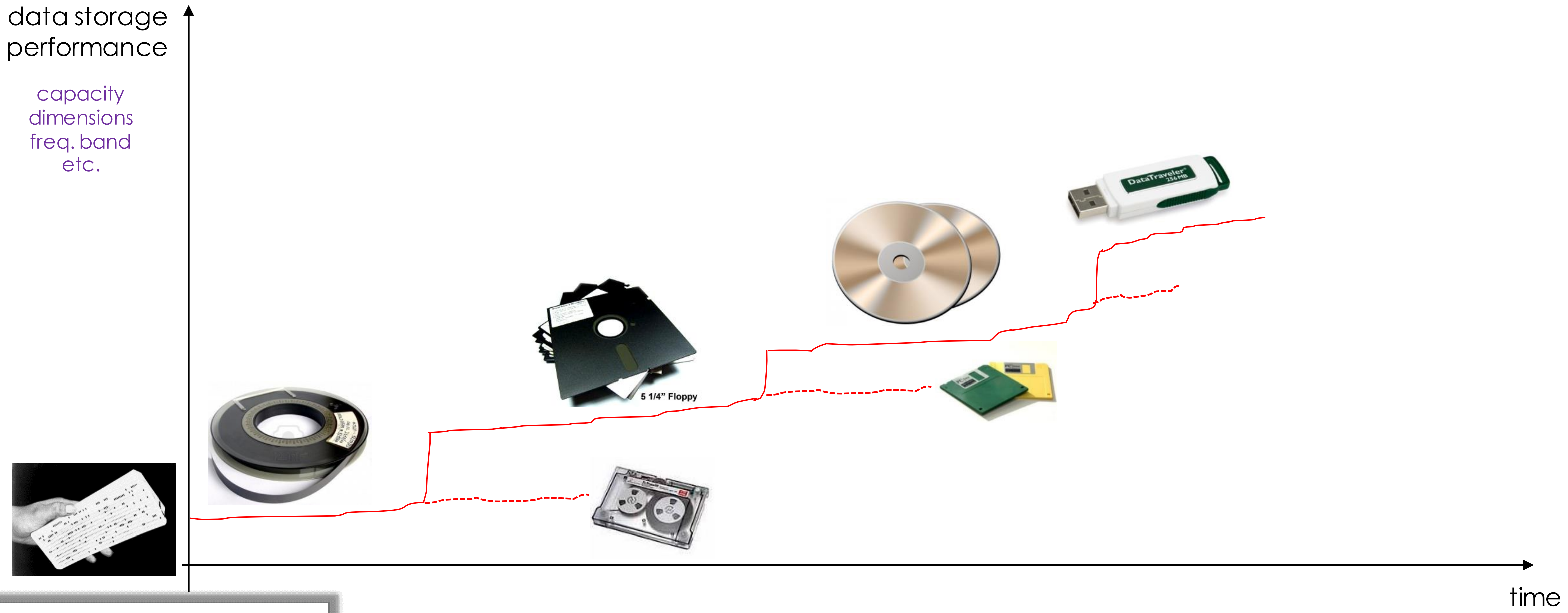
Technology evolution: incremental × disruptive...



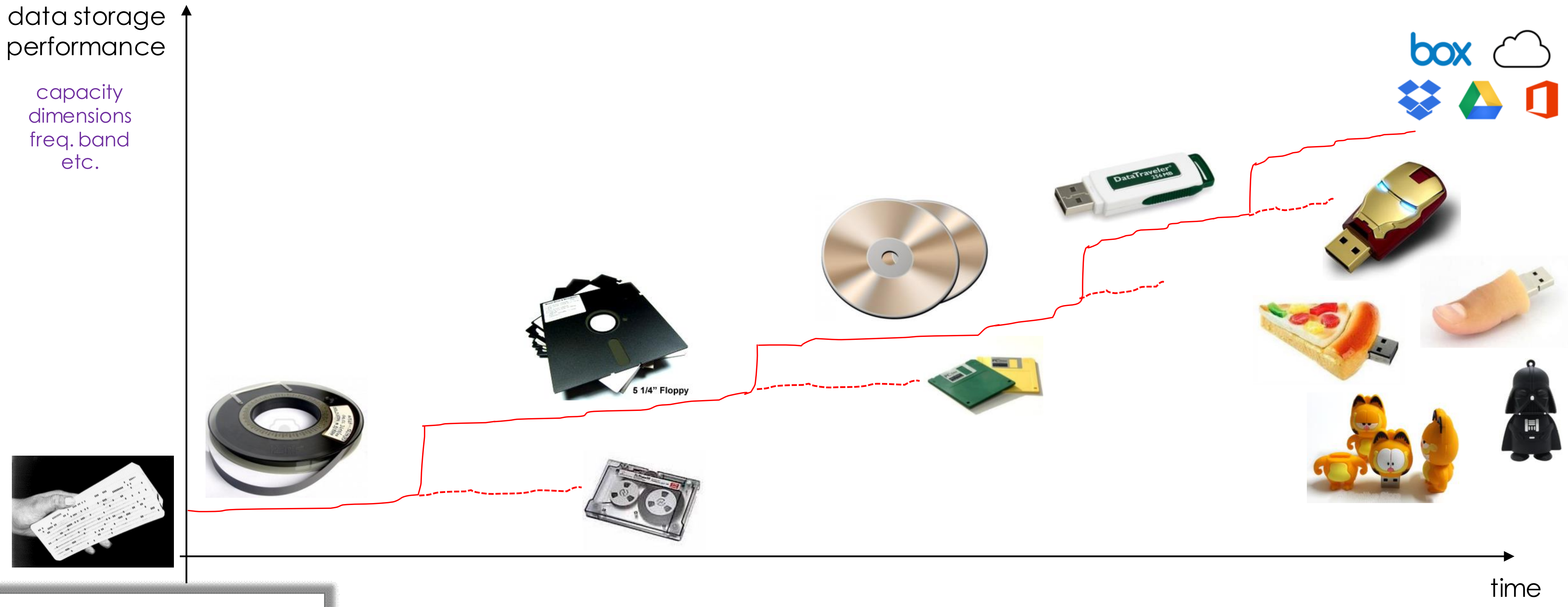
Technology evolution: incremental × disruptive…



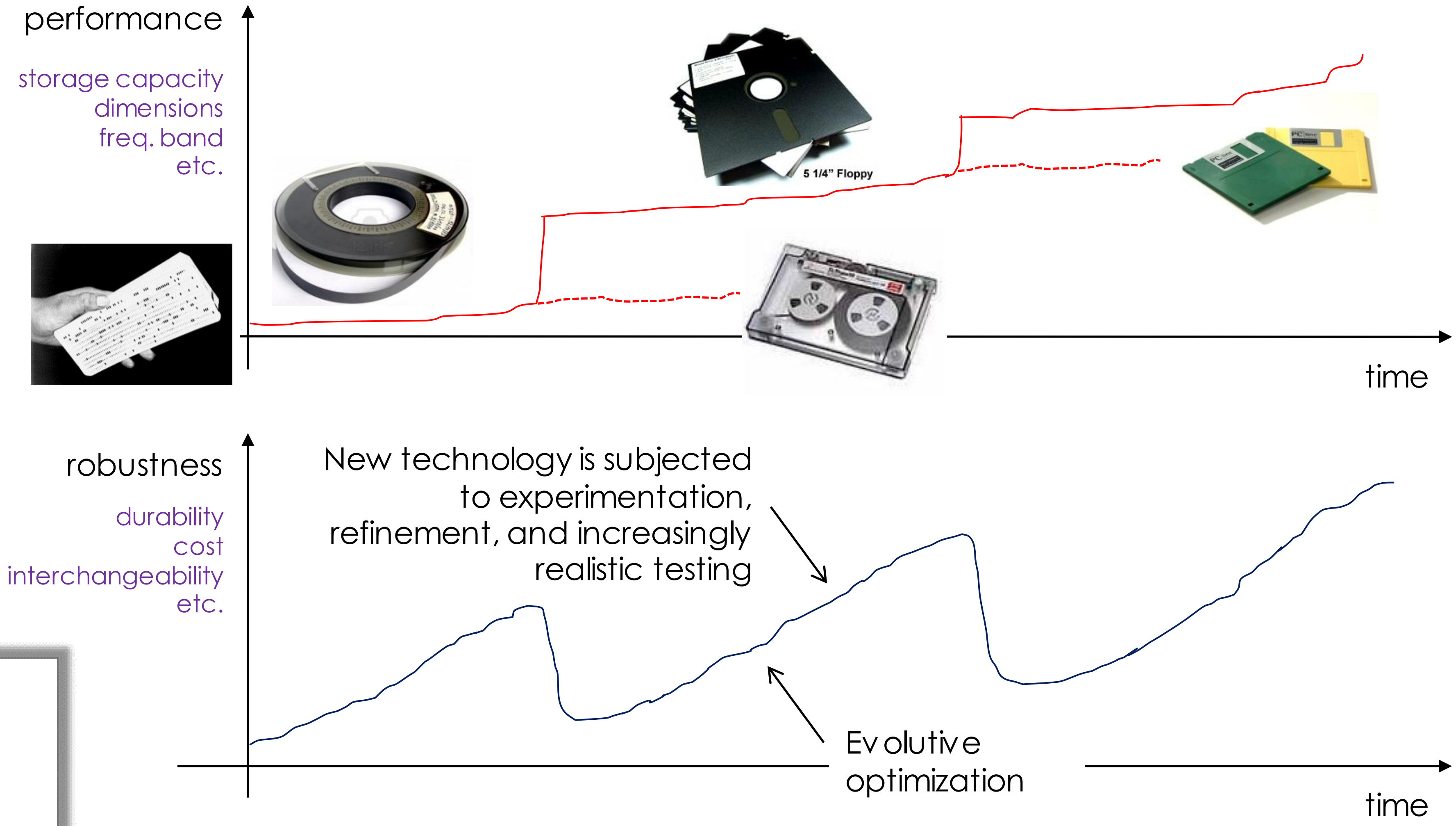
Technology evolution: incremental × disruptive...



Technology evolution: incremental × disruptive...

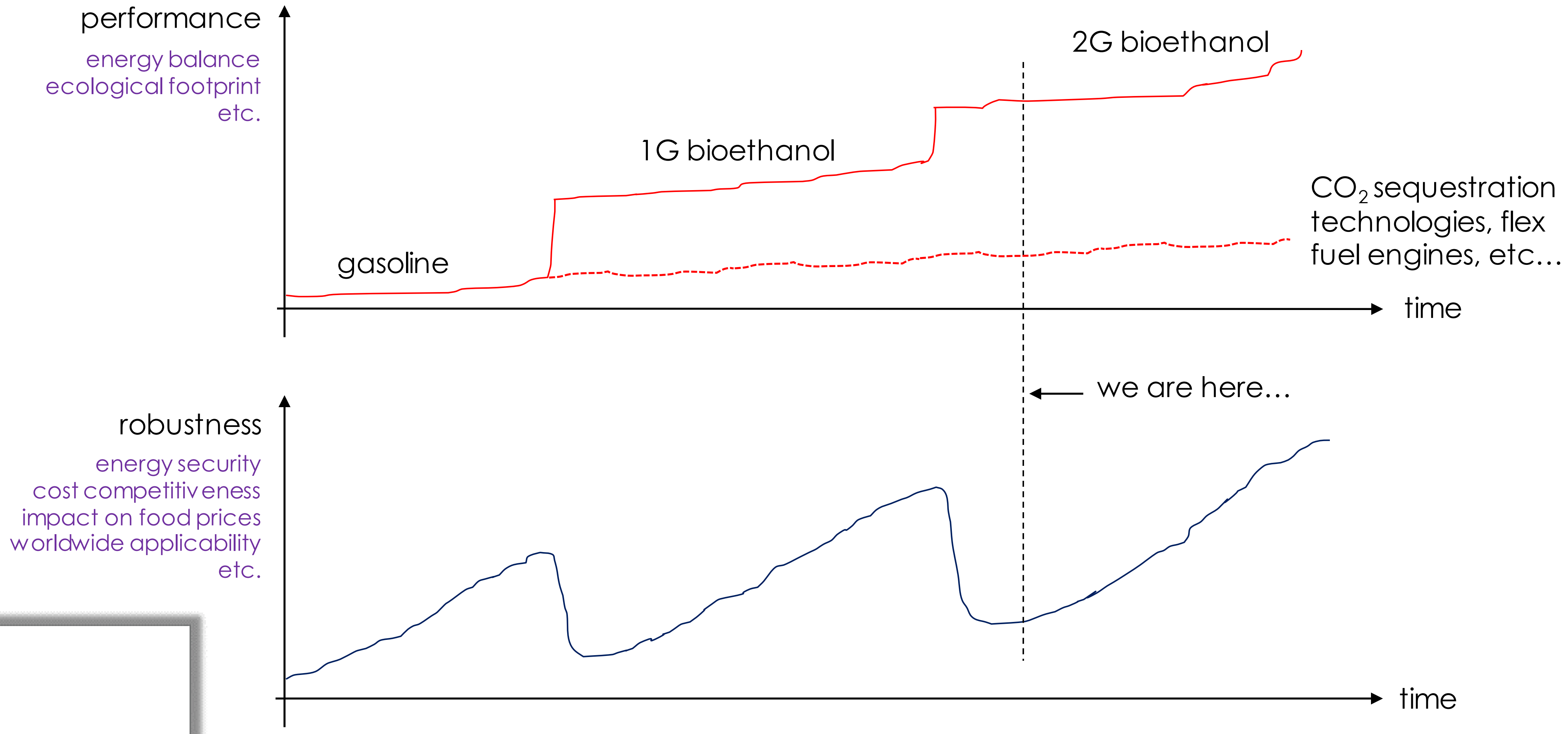


Technology evolution: performance × robustness...



How does this model applies to the development of liquid engine fuels ?

Engine liquid fuel technologies learning curves

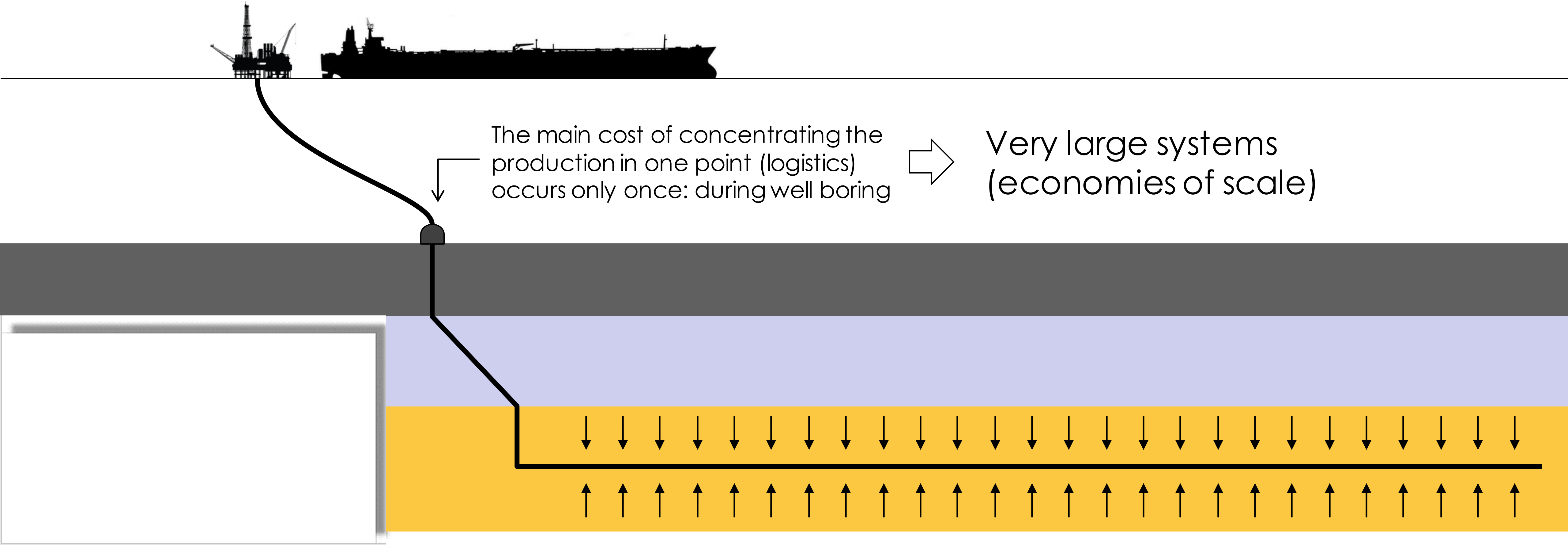


What have we learned from experience…

THE AGROINDUSTRIAL SYSTEM

What have we learned from experience…

Oil production systems… (economies of scale)



What have we learned from experience…

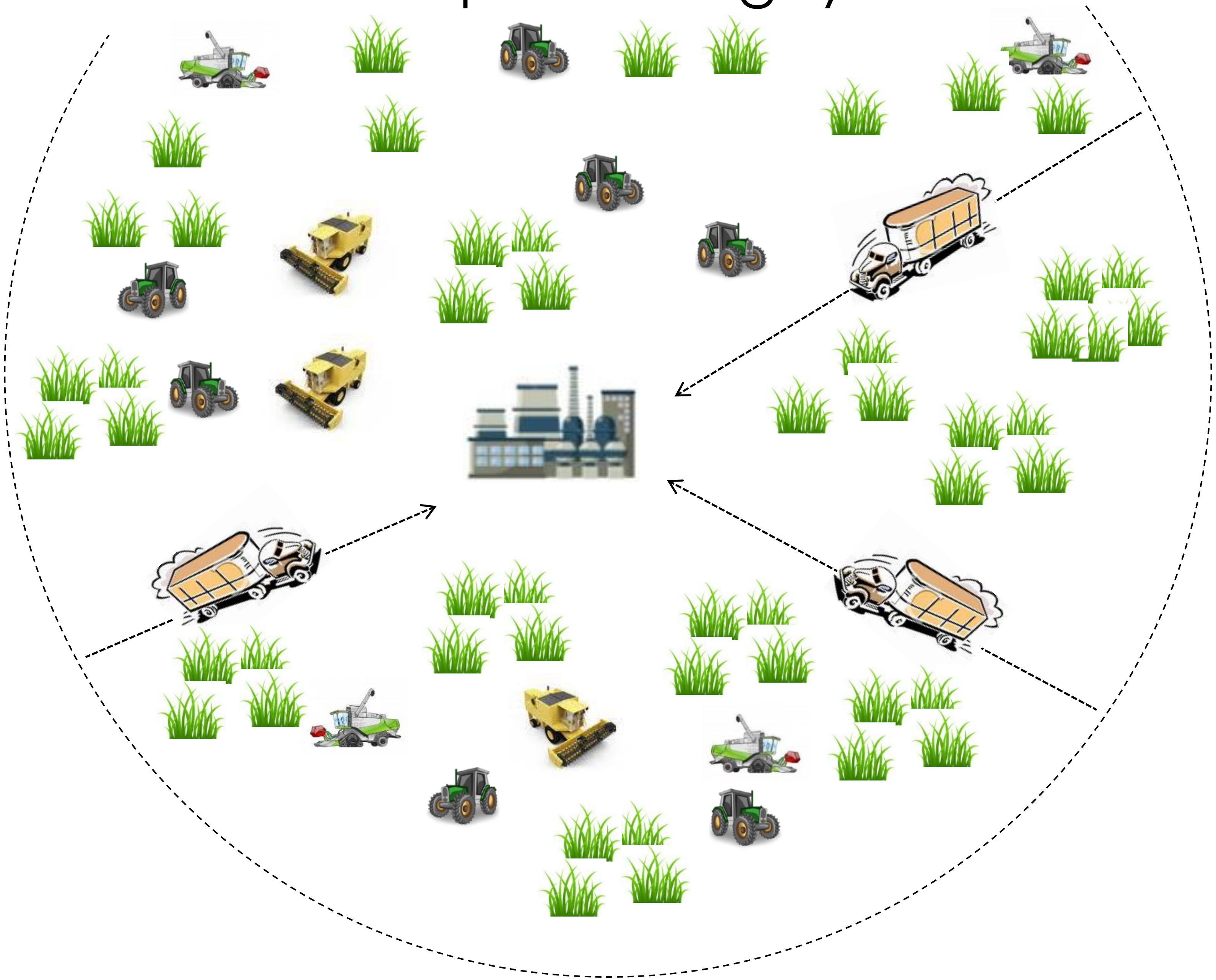
Biomass production systems…

… are always distributed over the production area !

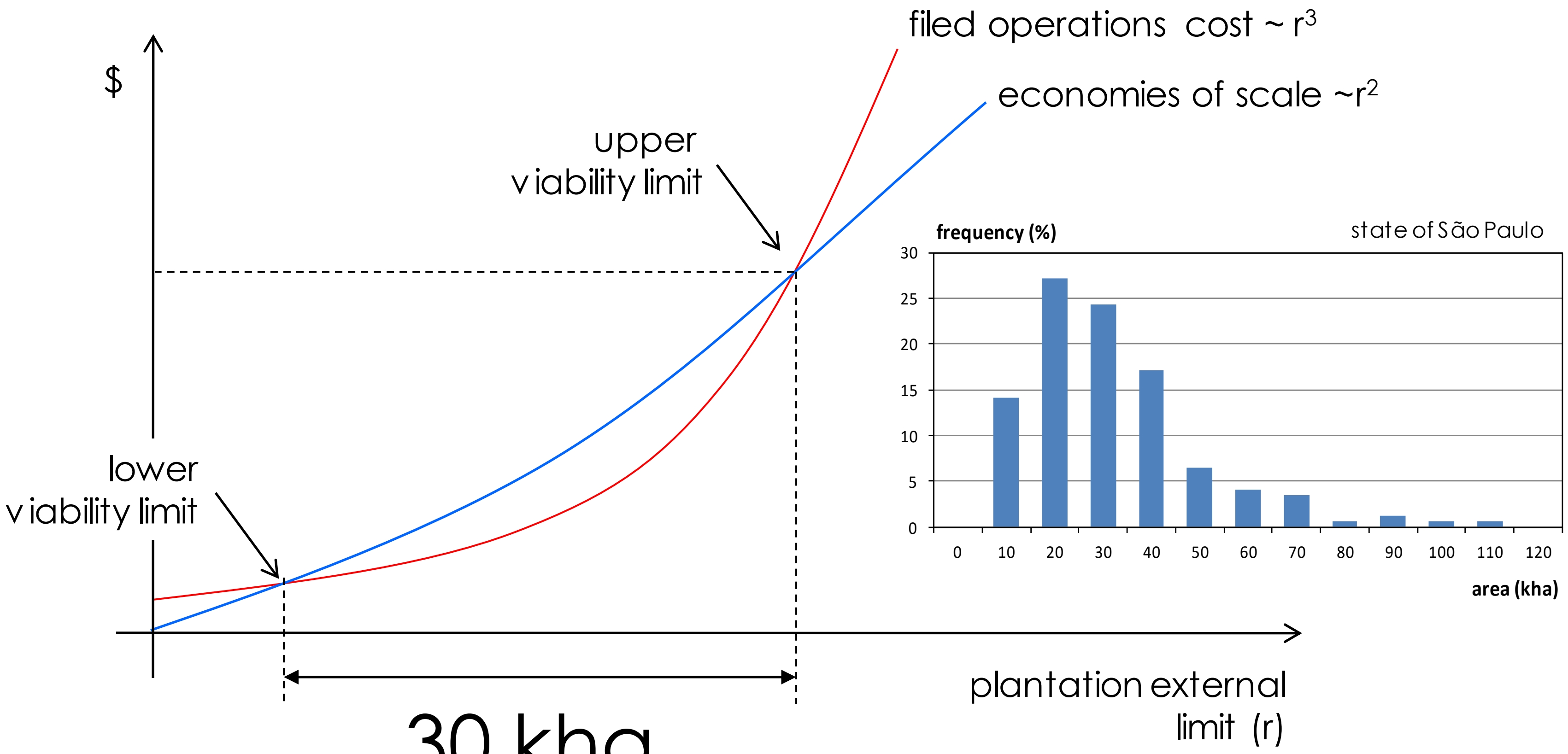
⇨ Medium to small scale systems, depending on the added value (economies of scale)

Biomass production and processing system

production
x
logistics
x
processing



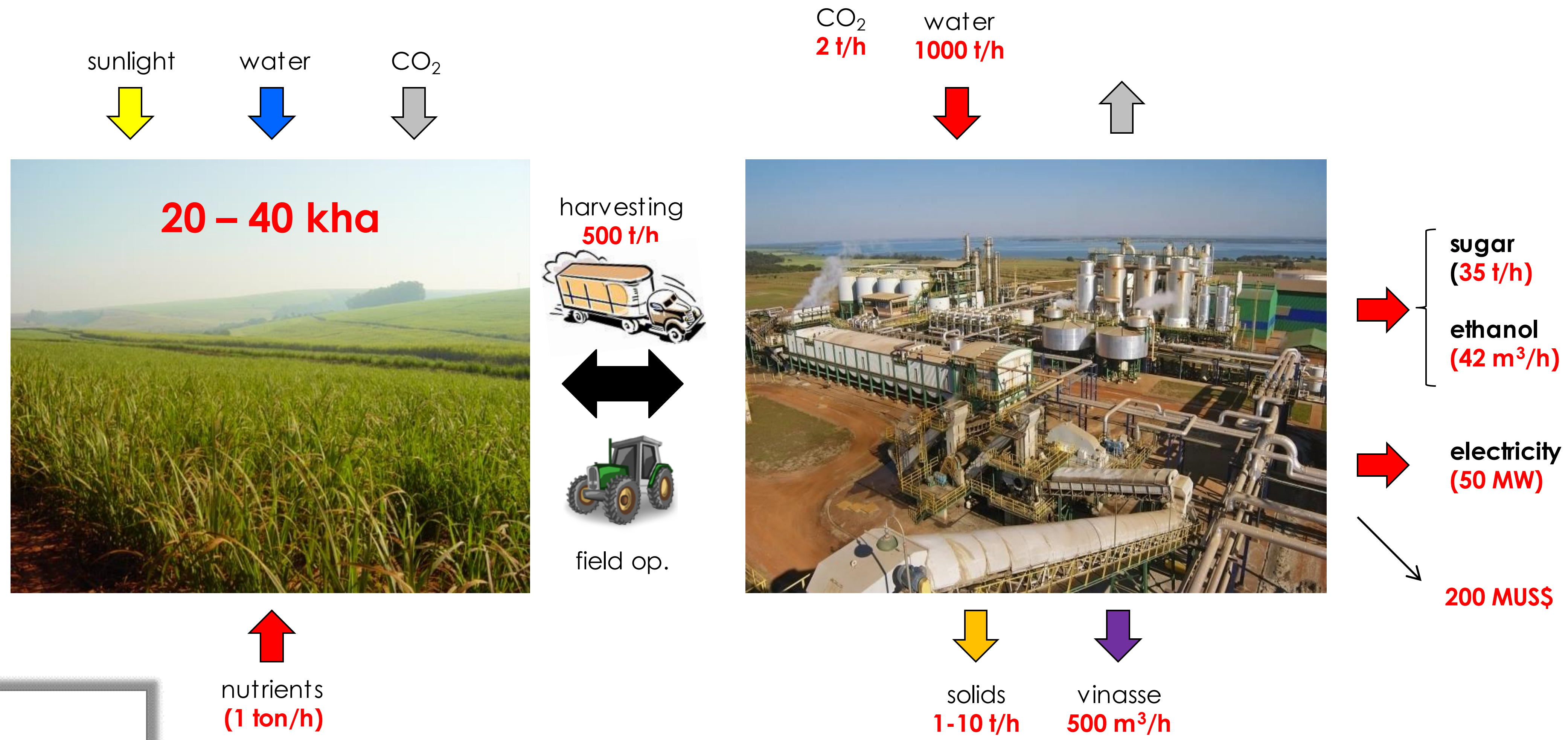
Sugarcane Production and Processing in Brazil



30 kha

500 tsc/h

Reference Sugarcane Production and Processing System



TRL 9 → “Turn Key” contracts

What have we learned from experience…

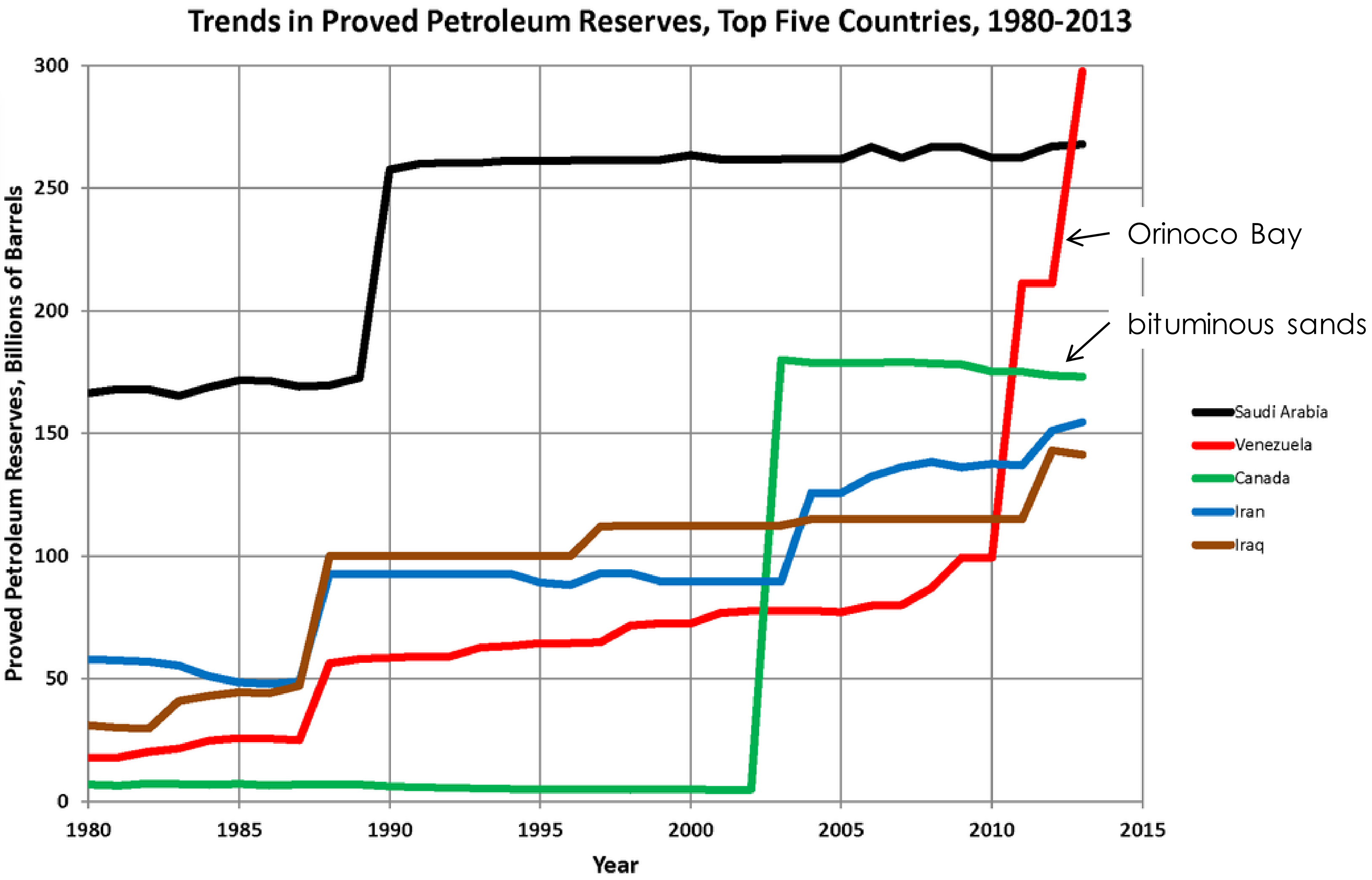
Incorporating new technologies increases the upper viability limit and, therefore, the overall economicity !

production ⟶ genetics, planting machines, etc.
x
logistics ⟶ whole harvesting machines, etc.
x
processing ⟶ extraction, water and energy balances, etc.

Case study: fuels and general purpose heat engines and electric motors

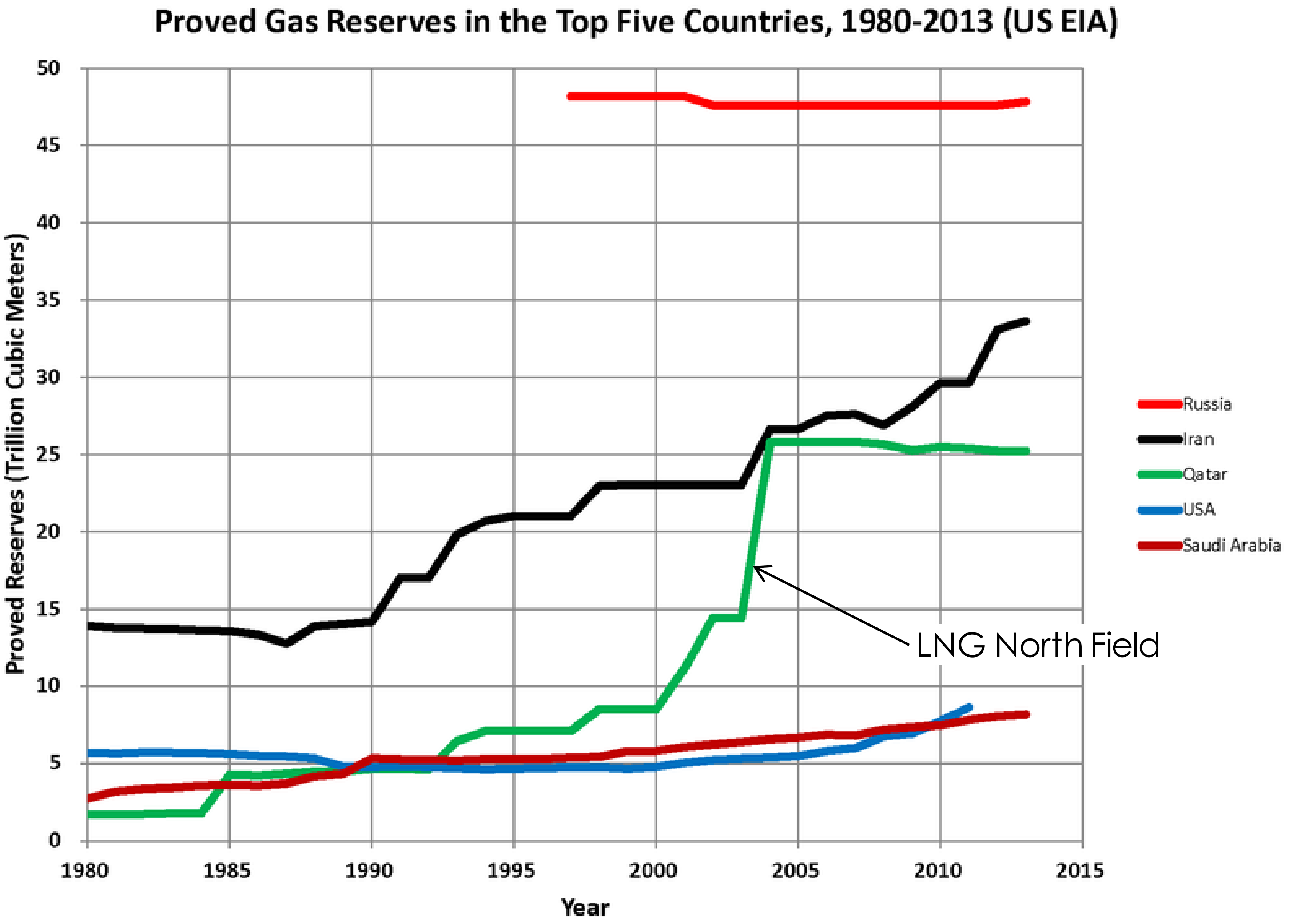
- Historical context and geopolitics of energy
- Theoretical framework
- Transitioning from the steam engine to the internal combustion and the electric motor
- Will biofuels displace fossil fuels ?

Historical context and geopolitics of energy



US Energy Information Administration

Historical context and geopolitics of energy



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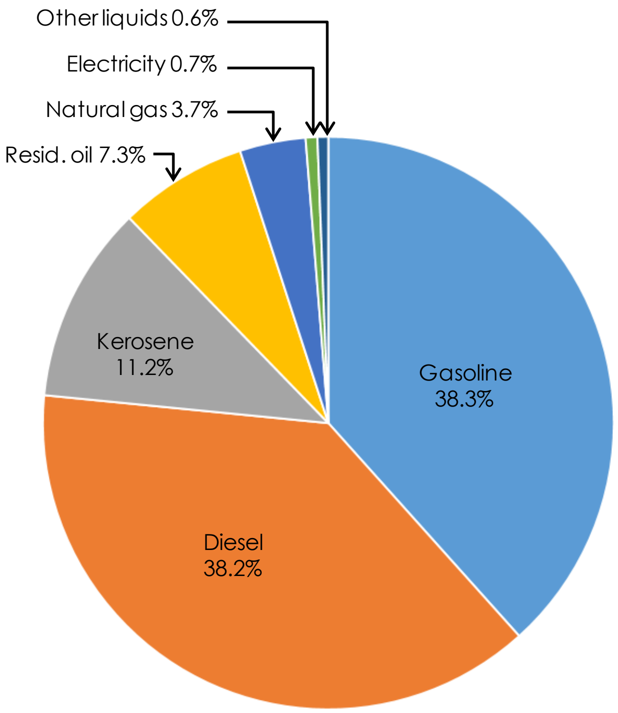


International Energy Outlook 2017

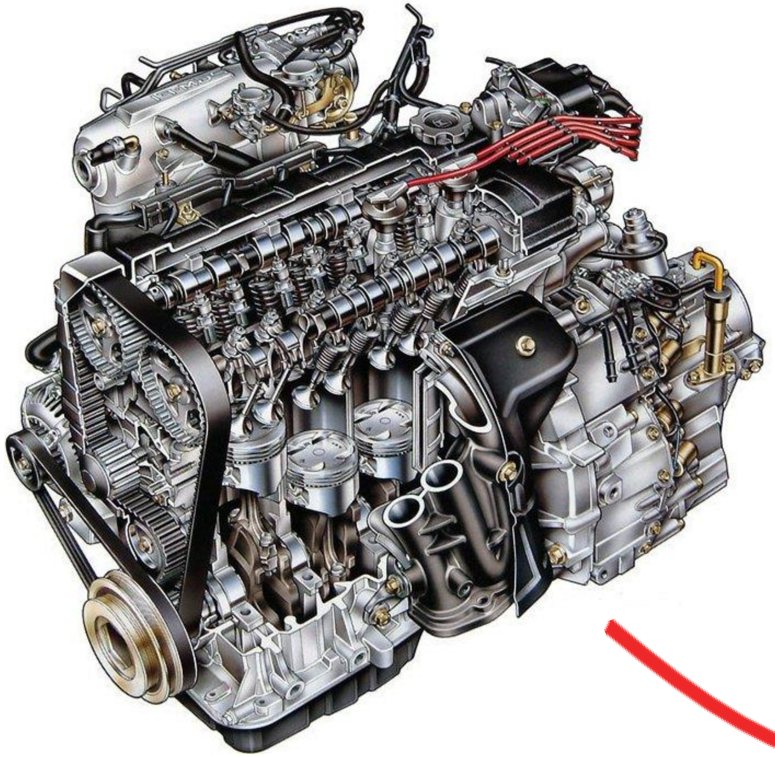
- The anticipated decline of the world's petroleum and gas production according to Hubbert's law have been proven premature
- Renewable energies compete economically and technically with fossil fuels
- In addition to competing, biofuels must adapt to the existing infrastructure developed originally for petroleum products (drop-in)
- Fossil sources will continue to be exploited with consequent intensification of CO_2 and other GHG emissions
- CCS techniques will play an important role…

Fuels and general purpose engines: theoretical framework

energy content $\longrightarrow$ $C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O +$ **heat**

mechanical energy (force × displacement)

heat lost to the environment



Chemical energy

Mechanical energy

Lost thermal energy

Fuels and general purpose engines: theoretical framework

Nicolas Léonard Sadi Carnot
in 1824, at 28 years

- Is it possible to convert 100% of the fuel's energy content to heat ? Yes, but…
- Is it possible to convert 100% of the generated heat to mechanical energy ? No, because…
- Is it possible not to reject heat to the environment ? No, because…
- What is the maximum conversion efficiency of heat to mechanical energy (work) ?

2nd Law of Thermodynamics

Fuels and general purpose engines: theoretical framework

Nicolas Léonard Sadi Carnot
in 1824, at 28 years

Battle of Waterloo fought in 06/18/1815
Duke of Wellington × Napoleon
by William Sadler

"Leur industrie est plus avancé ! "

Fuels and general purpose engines: theoretical framework

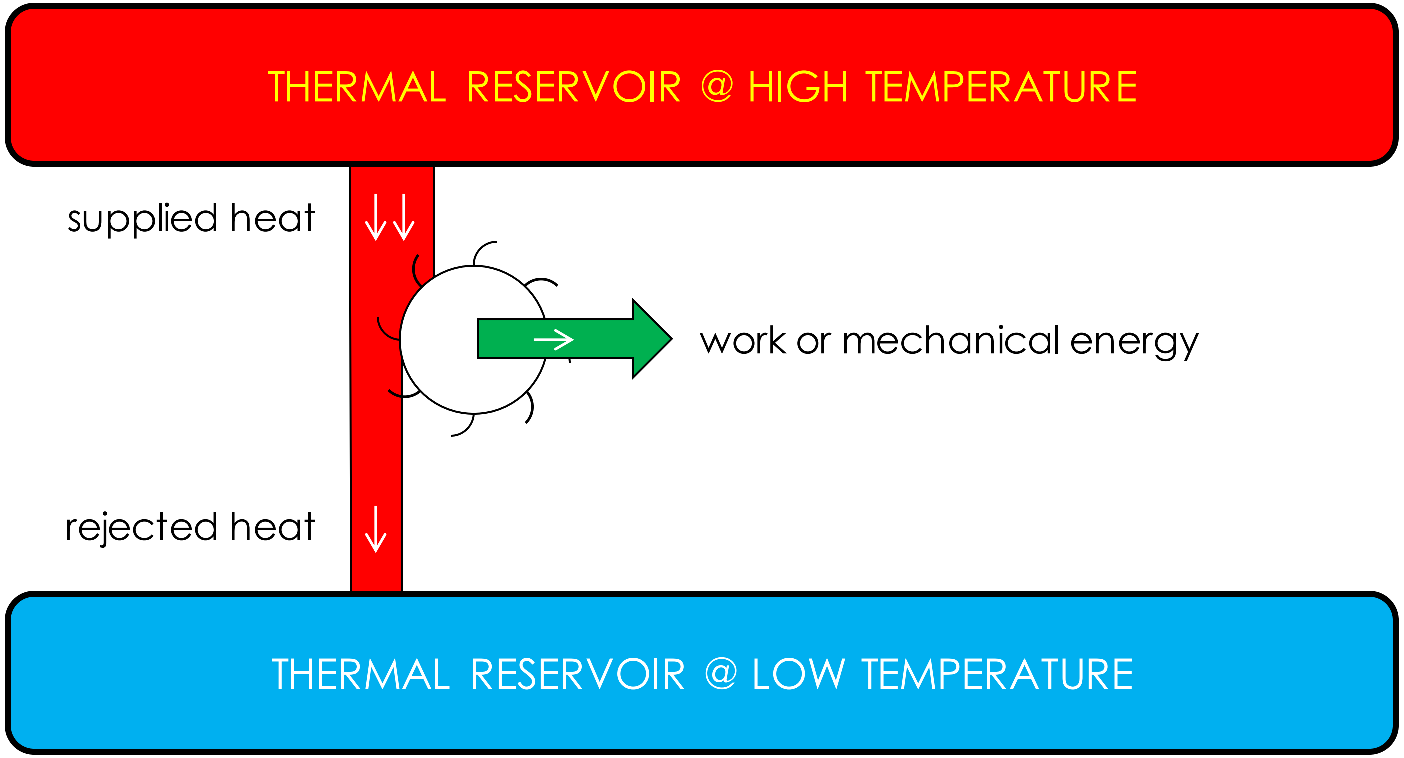
Nicolas Léonard Sadi Carnot
in 1824, at 28 years

"Le moteur peut être **actionné en sens inverse** et le résultat net serait alors que la consommation d'un **travail égal** à celui produit par le fonctionnement en sens direct et le **transfert de la même quantité de chaleur**, mais, dans ce cas, du corps froid au corps chaud..."

Maximum conversion efficiency occurs when the process is strictly reversible !

How to know if a process is strictly reversible ?

Nicolas Léonard Sadi Carnot
in 1824, at 28 years



1st law efficiency or
thermodynamic efficiency

$$\eta \overset{\text{def}}{=} \frac{\text{work}}{\text{supplied heat}} \overset{\text{1st Law}}{=} 1 - \frac{\text{rejected heat}}{\text{supplied heat}}$$

How to know if a process is strictly reversible ?

Nicolas Léonard Sadi Carnot
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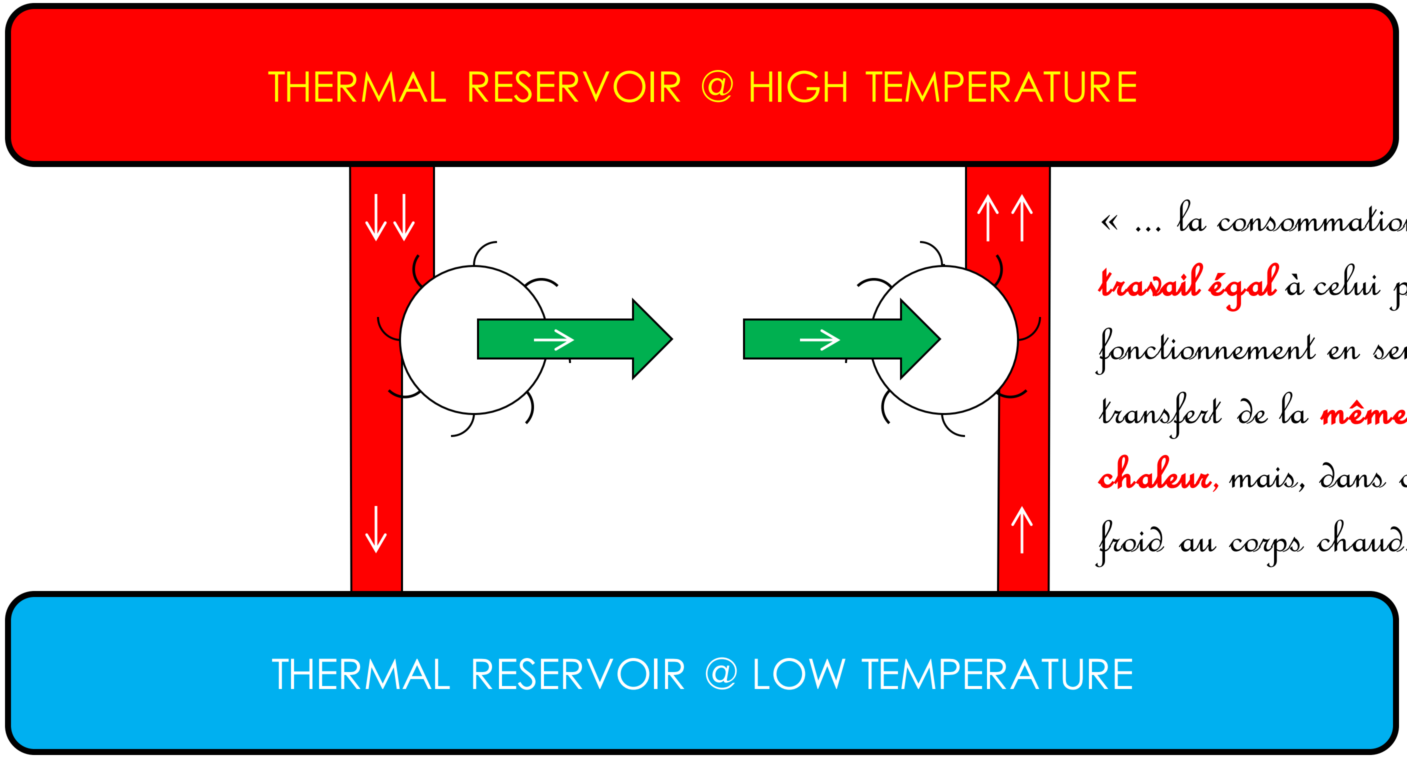
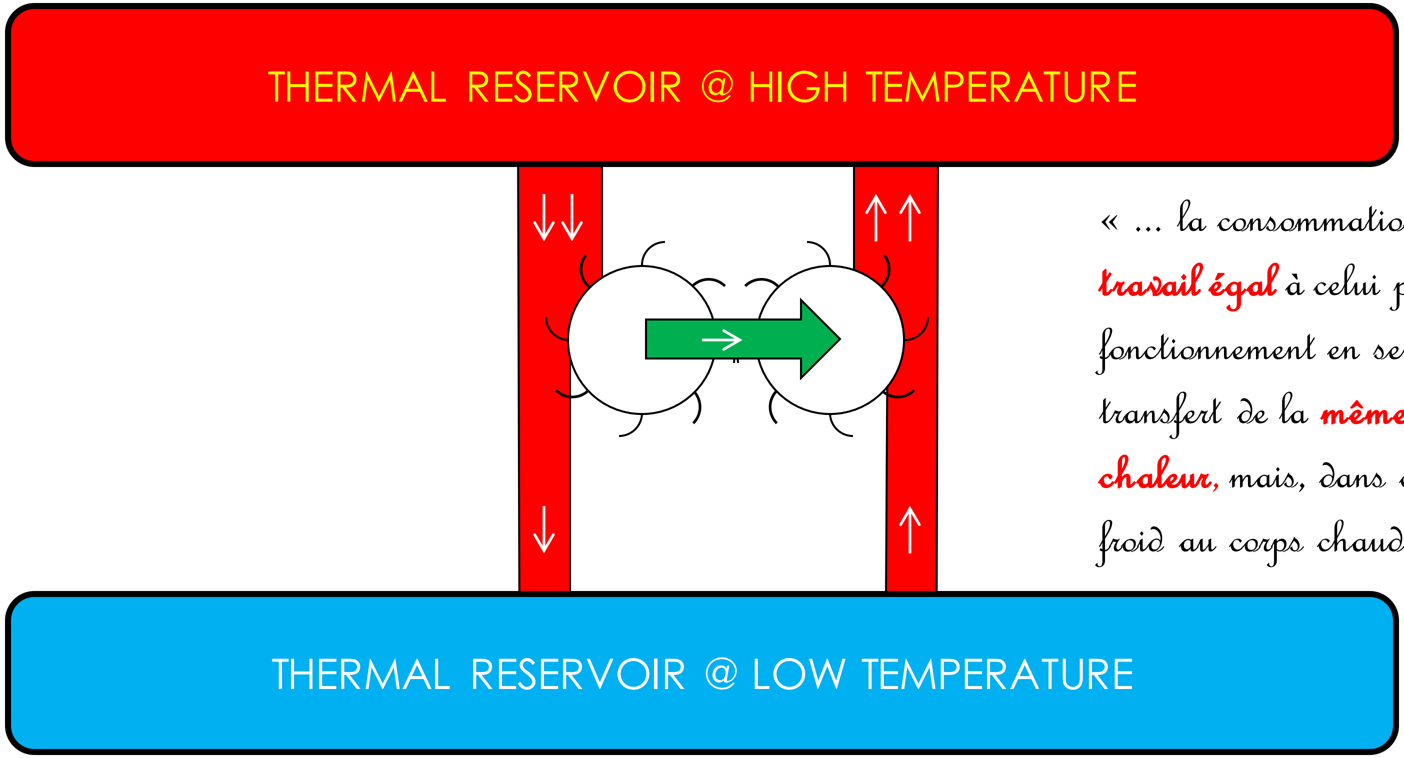


« … la consommation d'un **travail égal** à celui produit par le fonctionnement en sens direct et le transfert de la **même quantité de chaleur**, mais, dans ce cas, du corps froid au corps chaud…"

$$\eta \overset{\text{def}}{=} \frac{\text{work}}{\text{supplied heat}} \overset{\text{1st Law}}{=} 1 - \frac{\text{rejected heat}}{\text{supplied heat}}$$

How to know if a process is strictly reversible ?

Nicolas Léonard Sadi Carnot
in 1824, at 28 years



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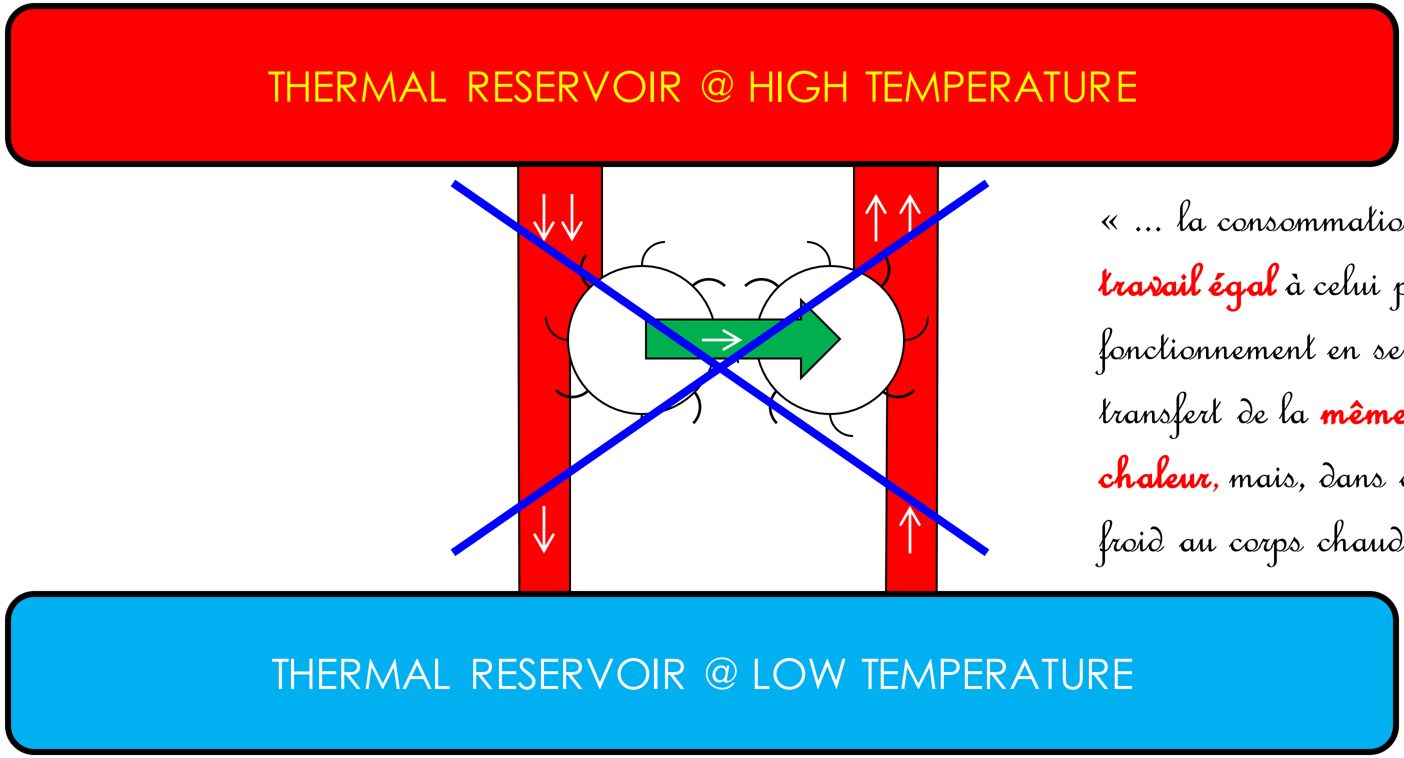

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THERMAL RESERVOIR @ HIGH TEMPERATURE

$$\eta = \eta_{max}$$

THERMAL RESERVOIR @ LOW TEMPERATURE

$$\eta \overset{def}{=} \frac{\text{work}}{\text{supplied heat}} \overset{1st\,Law}{=} 1 - \frac{\text{rejected heat}}{\text{supplied heat}}$$

Summary of Carnot's findings about conversion efficiency:

Nicolas Léonard Sadi Carnot
in 1824, at 28 years

- $\eta < 1$ for $\Delta T < \infty$
- $\eta_{rev} > \eta_{irrev}$
- $\eta_{rev,m} = \eta_{rev,n} \; \forall \; m,n$
- $\eta_{rev} = f(\,T_{hot}\,,\,T_{cold}\,)$

$$\Rightarrow \eta_{rev} = 1 - T_{cold} / T_{hot} = 1 - \frac{1}{1 + \Delta T / T_{env}}$$

Kelvin
Rankine

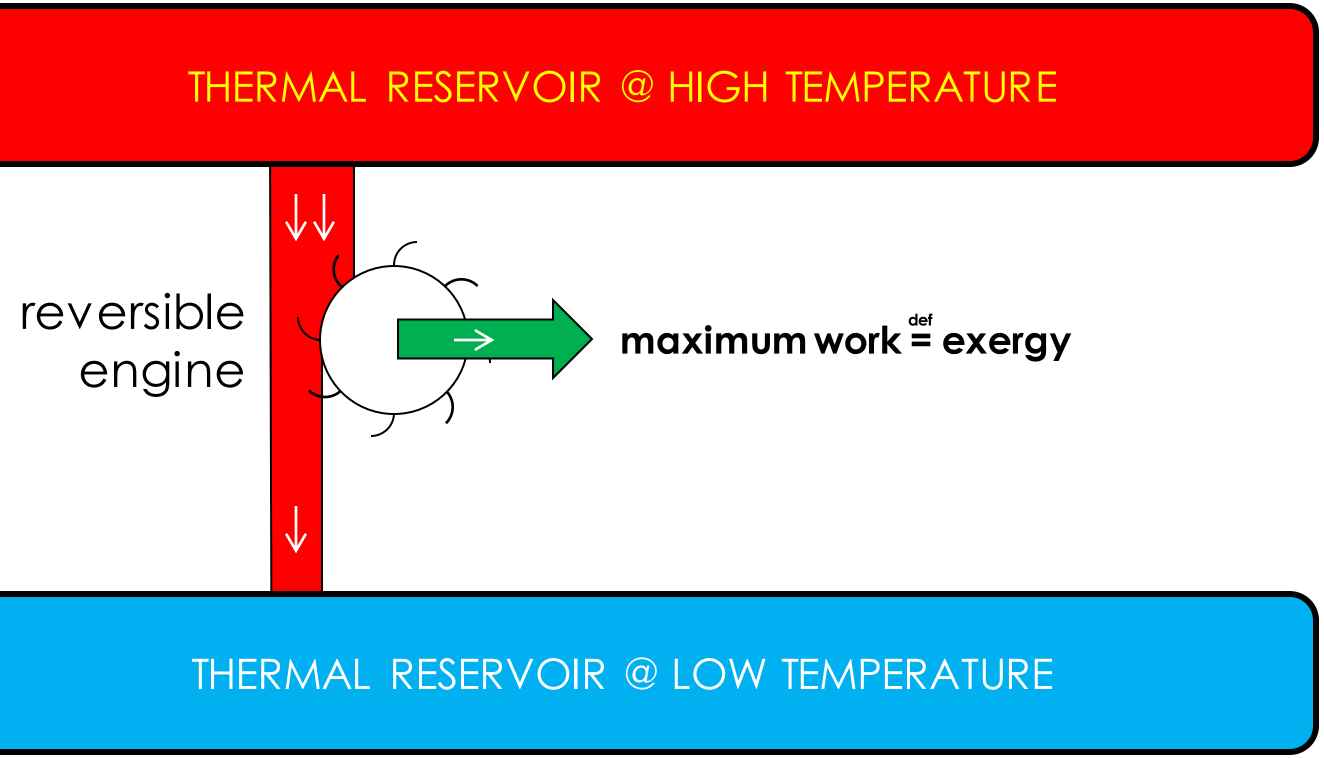
$T_{cold} = T_{env}$

$T_{hot} = T_{cold} + \Delta T$

It is the temperature difference between the thermal reservoirs that influences the efficiency, and not the pressure as it was commonly accepted…

Summary of Carnot's findings about conversion efficiency:

Nicolas Léonard Sadi Carnot
in 1824, at 28 years

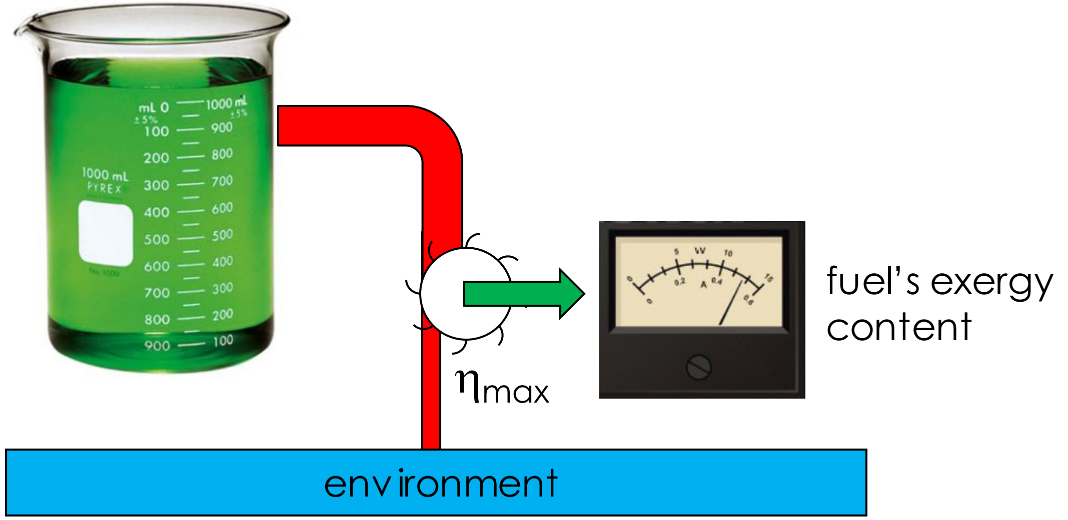


$$\eta_{max} = \eta = \frac{\text{work}}{\text{supplied heat}} \Rightarrow$$ maximum work per unit supplied heat (fuel)

Some important concepts related to exergy:

Nicolas Léonard Sadi Carnot
in 1824, at 28 years

- Exergy is defined as the maximum work obtained from an energy source through a eversible machine…
- To determine the exergy content of an energy source (heat, substance, etc.) use it to drive a reversible machine… (“exergymeter”)



Typical maximum conversion efficiency in IC engines

Nicolas Léonard Sadi Carnot
in 1824, at 28 years

Chemical energy

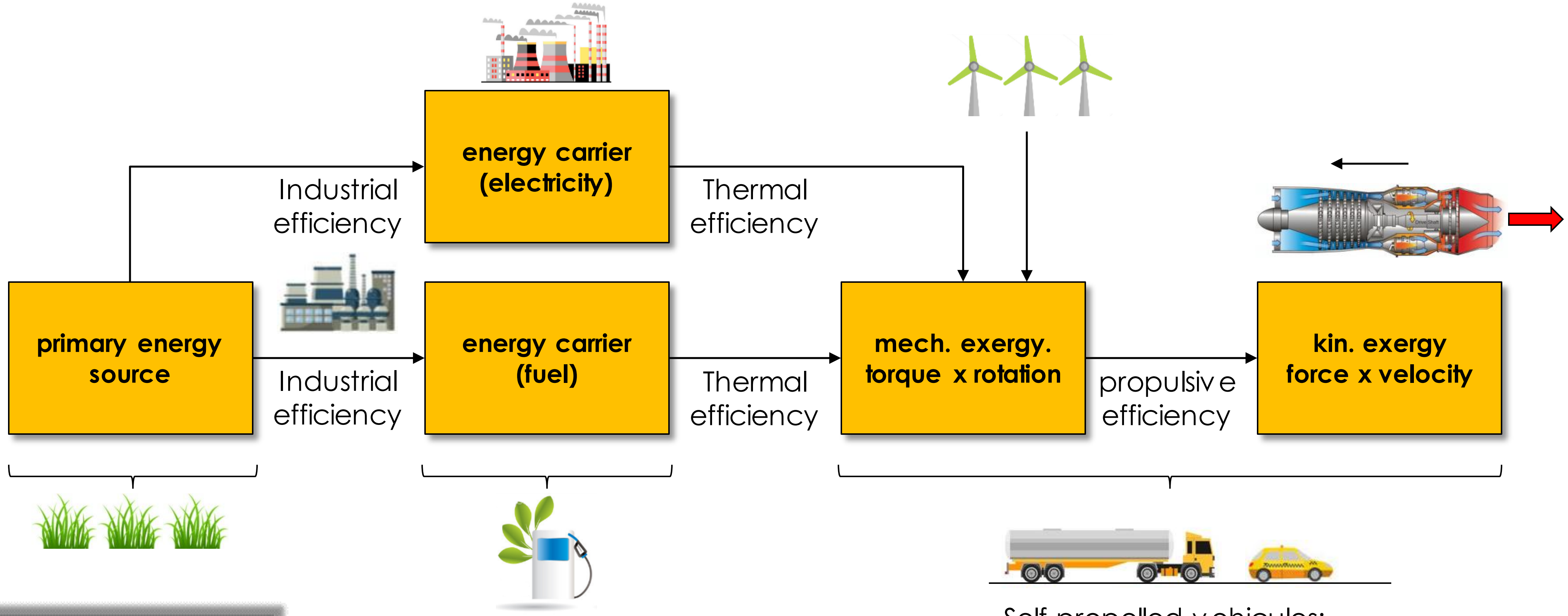
Mechanical energy

Lost heat
T_{env} = 30°C

$$\eta_{max} = 1 - T_{cold} / T_{hot} = 1 - \frac{30 + 273}{600 + 273} = 65.3\%$$

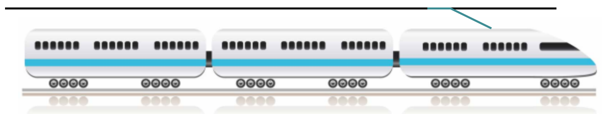
$30 - 40\% \leftarrow$ Typical

Energy transformations and use in the transportation sector



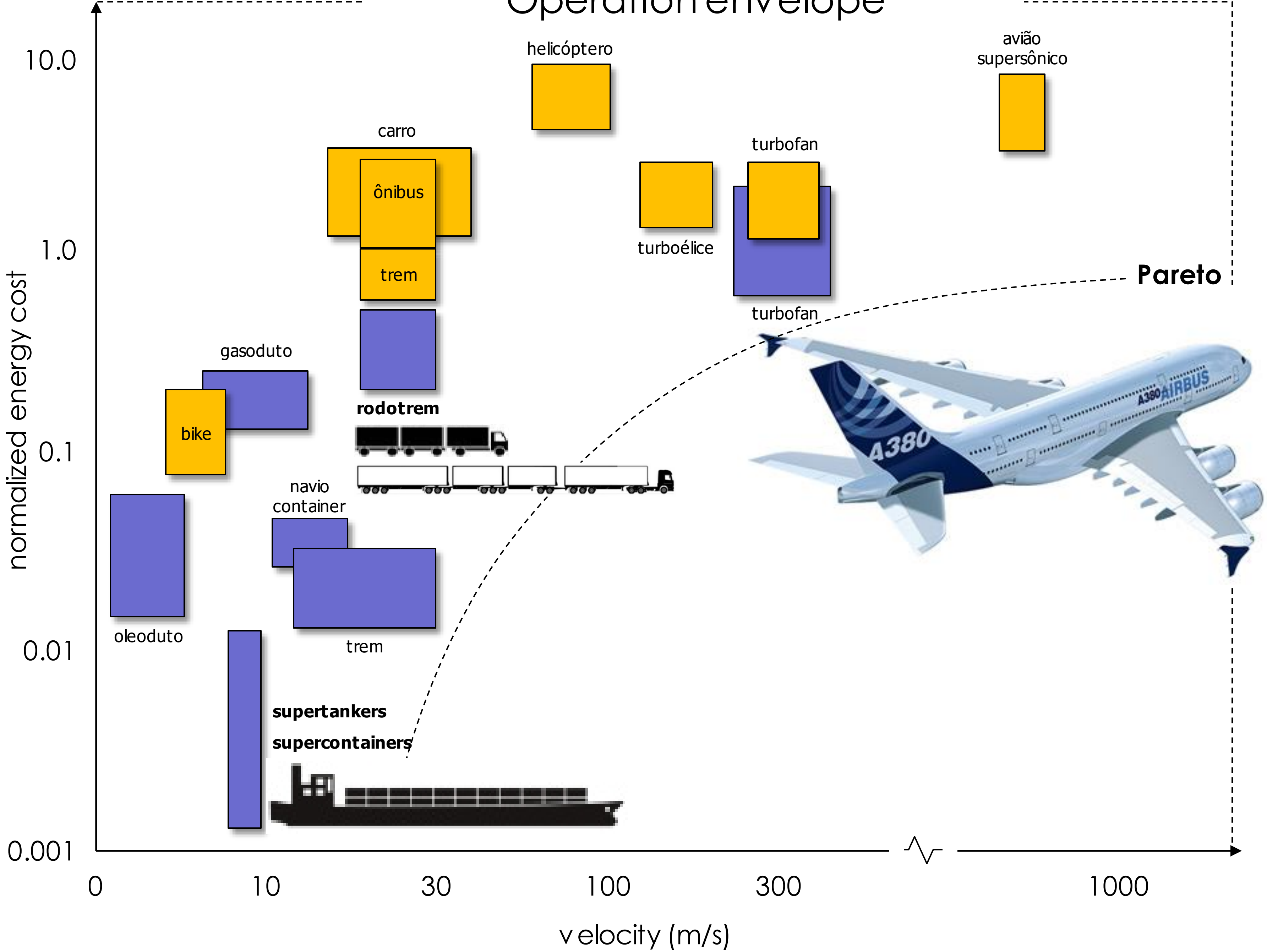
Self propelled vehicules:

- **Energy storage**
- **Powertrain (motor +... wheels)**



Demand / Modal

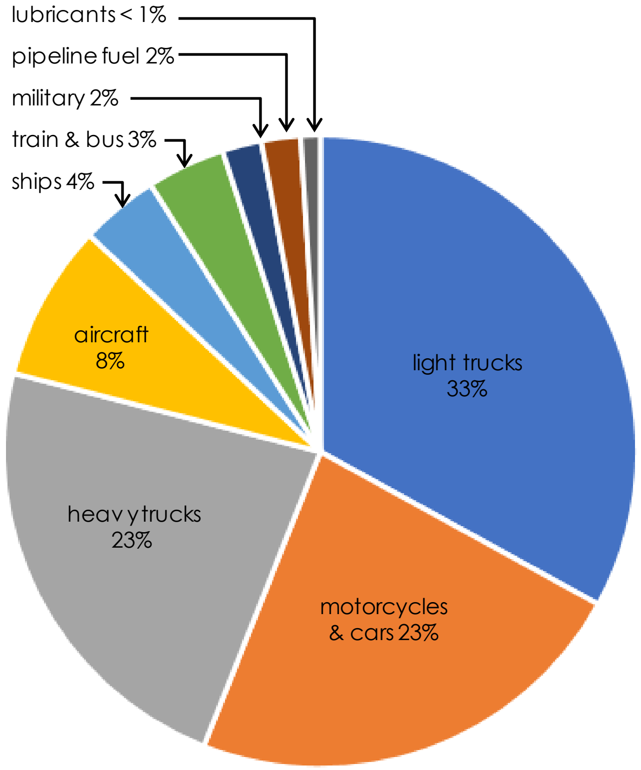
Operation envelope



http://sia.planning.unc.edu/

consumo ~ atrito ~velocidade ~ área externa
capacidade de transporte ~ volume

Will biofuels displace fossil fuels in the transportation sector ?



International Energy Outlook 2017

- Diesel engine fuels for high power engines (>1000 HP) are still in the early stages deployment (TRL 6 – 7) due to feedstock issues
- Biokerosene (Brayton) is still in the process of technological development associated with its certification as an aviation fuel
- Industrial processes of biomass conversion to biofuels for Otto engines must evolve to TRLs 8 -9
- Overall economicity must be improved by integrating new technologies to enable larger scale systems

Biorefineries: development status and perspectives

- Initiatives around the world
- Timeline and current (reported) TRL status
- Turning obstacles into opportunities: challenges in feedstock production and conversion processes

Liquid biofuels from biomass – Task 39 IEA Bioenergy

Type

- TRL 1-3 Research
- TRL 4-5 Pilot
- TRL 6-7 Demonstration
- TRL 8 First-of-a-kind commercial demo
- TRL 9 Commercial

Technology

- - Gasification
- - Fast Pyrolysis
- - - Hydrothermal Liquefaction
- - Fermentation
- - Hydrotreatment
- - Other Technology

Status

- no status
- - planned
- - under construction
- - operational
- - - cancelled
- - - stopped while under construction
- - - idle
- - - deconstructed
- - - on hold

- operational | - under construction | - planned | - non operational | no status

bioenergy2020+

http://demoplants.bioenergy2020.eu/

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Liquid biofuels from biomass – Task 39 IEA Bioenergy

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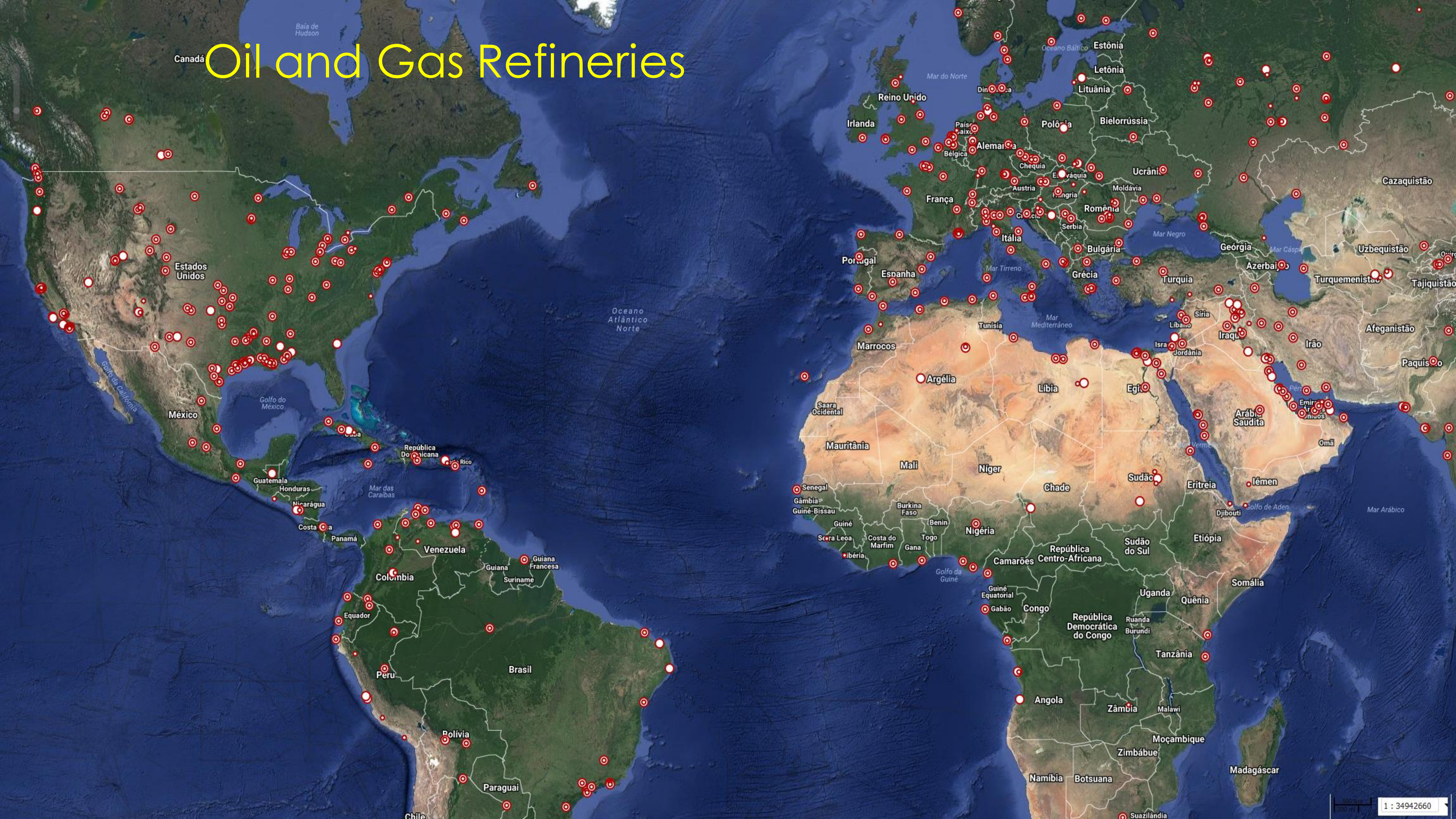
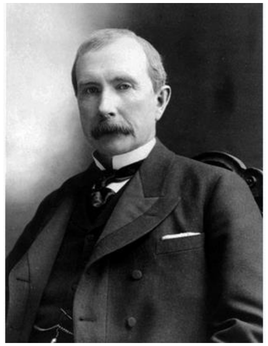
Oil and Gas Refineries



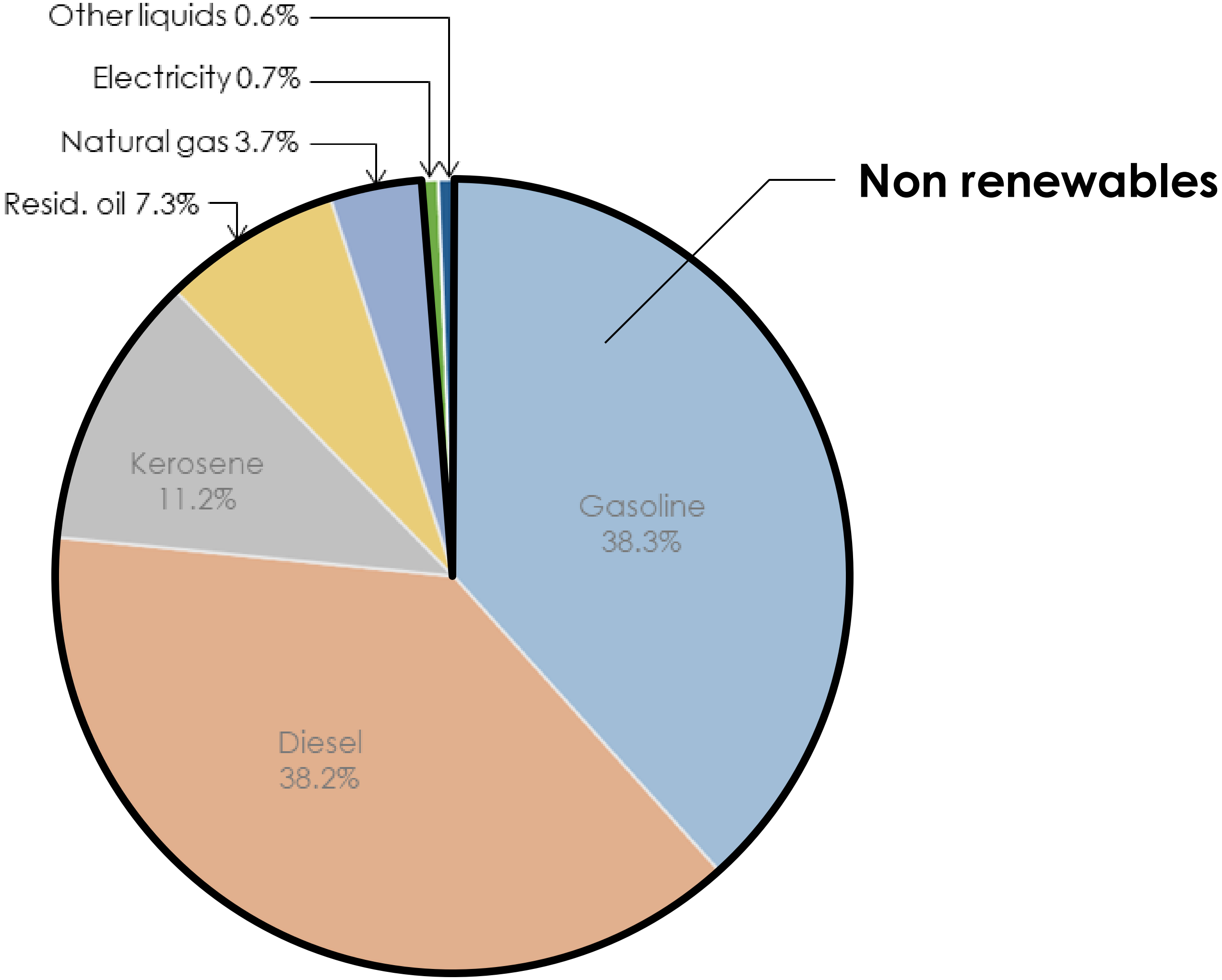
Current energy vectors used in the transportation sector

Calouste Sarkis Gulbenkian
1869 - 1955



John Davison Rockefeller
1839 - 1937

Sir Winston Churchill
1874 - 1965



International Energy Outlook 2017

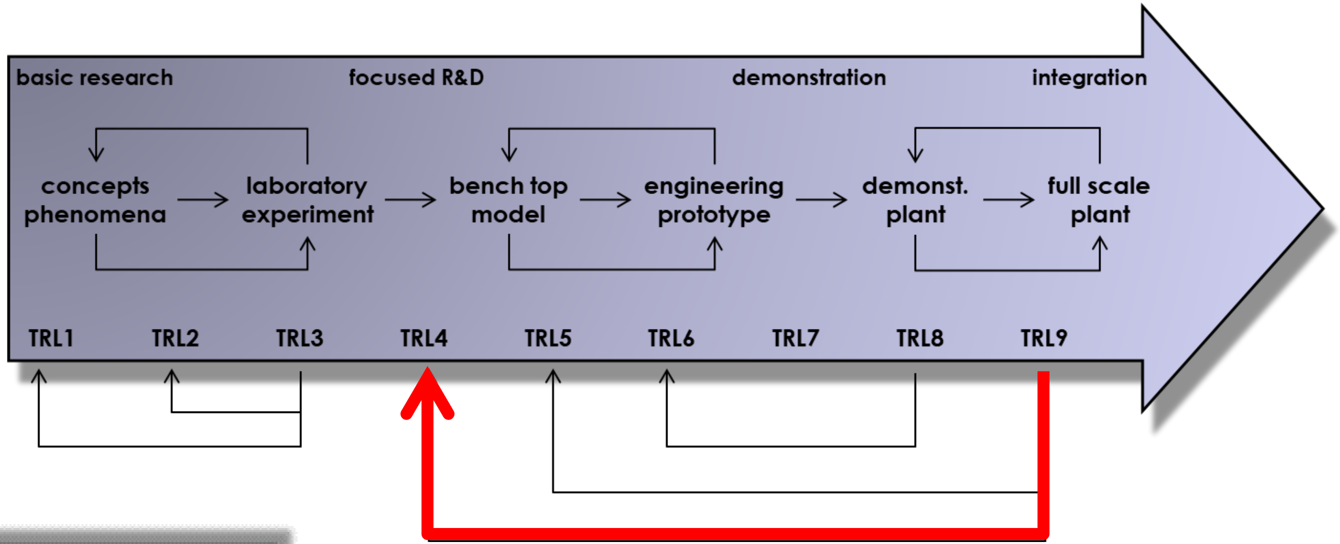
Learning through experience naturally drives improvements through **reinforcing feedbacks** to technology reevaluation at all levels...

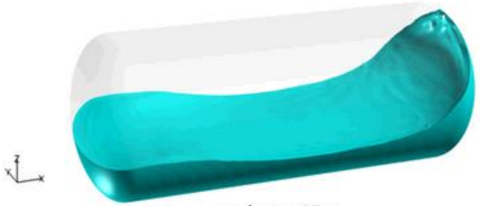
…although TRLs are classified progressively, **technology evolves in cycles of reevaluation** rather than in a straight temporal line.

Zoroaster the first tanker ship

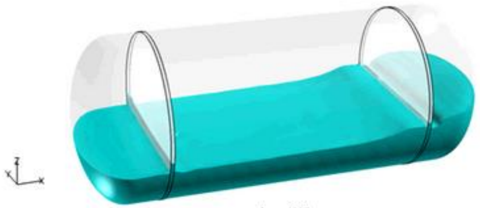
sloshing

inadequate materials





w/o baffle



w baffle

Obstacles and problems are opportunities…

whole harvesting techniques
robust root system
planting machines for sc
etc.

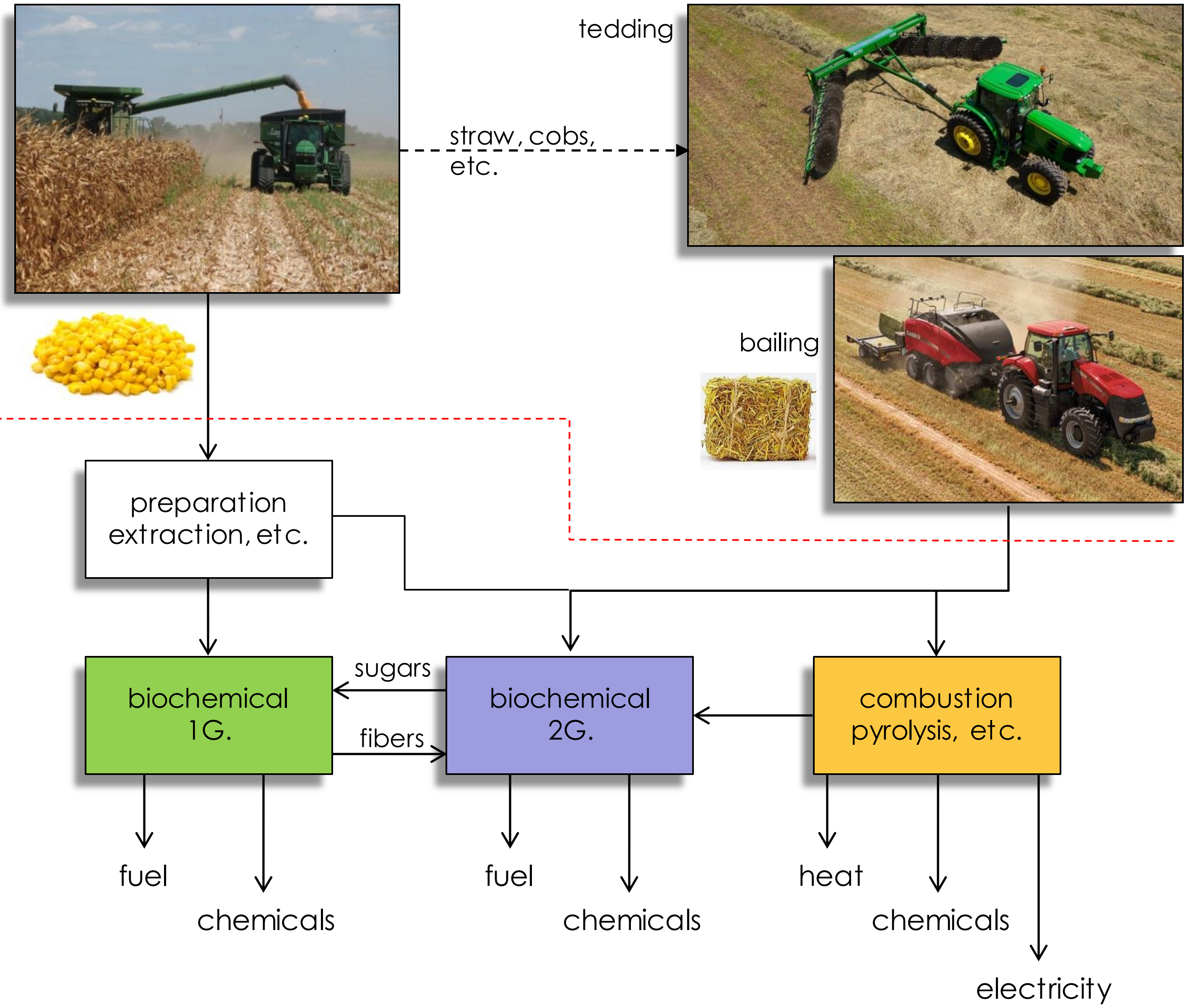
Production

road trains
low soil compaction tires
etc.

Logistics

efficient separation
high performance extraction
enzymes production
etc.

Processing



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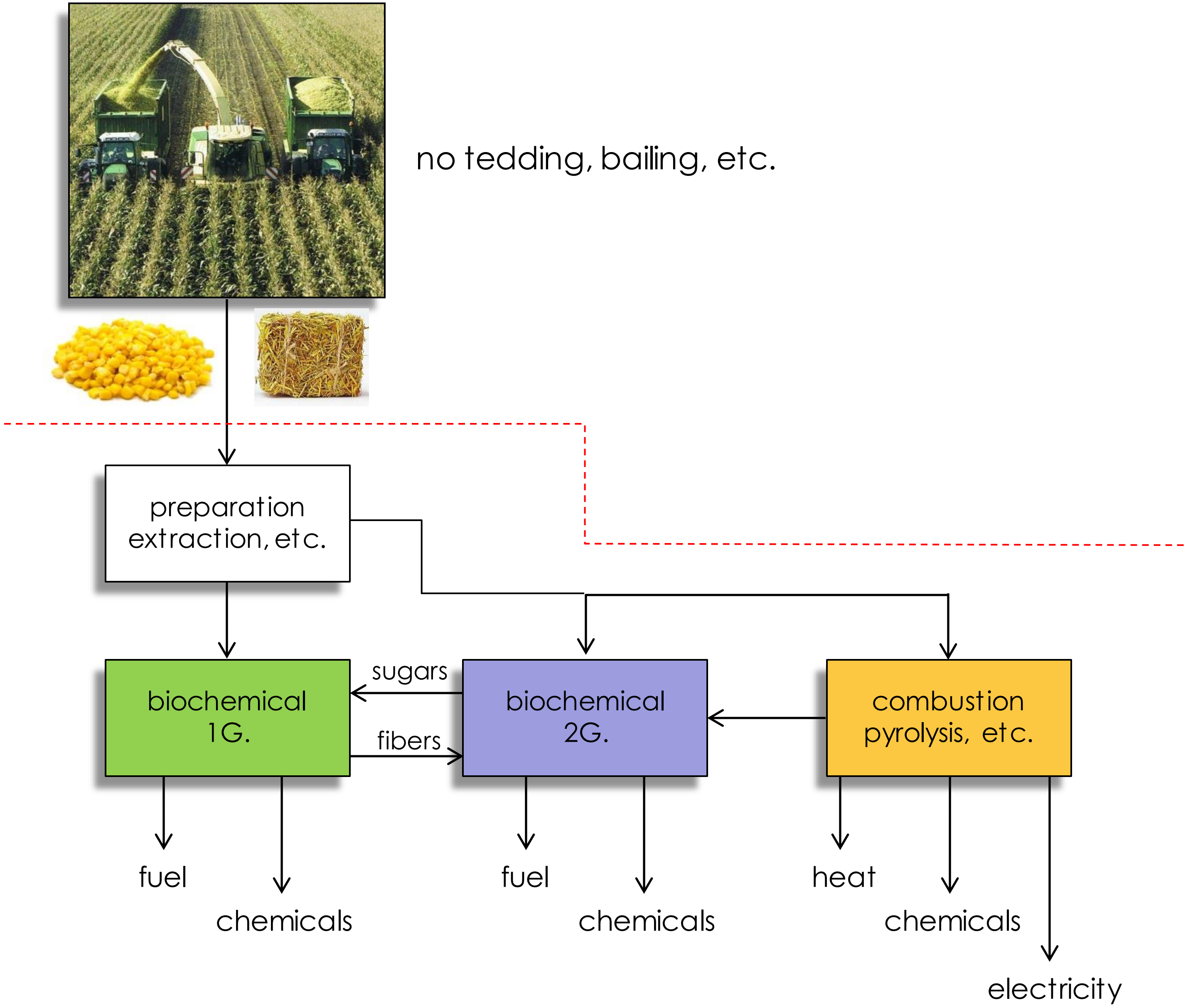


Obstacles and problems are opportunities…

whole harvesting techniques
robust root system
planting machines for sc
etc.

Production

no transshipment

road trains
low soil compaction tires
etc.

Logistics

preparation
extraction, etc.

efficient separation
high performance extraction
enzymes production
etc.

Processing

biochemical
1G.

sugars

fibers

biochemical
2G.

combustion
pyrolysis, etc.

fuel

chemicals

fuel

chemicals

heat

chemicals

electricity

Obstacles and problems are opportunities…

whole harvesting techniques
robust root system
planting machines for sc
etc.

Production

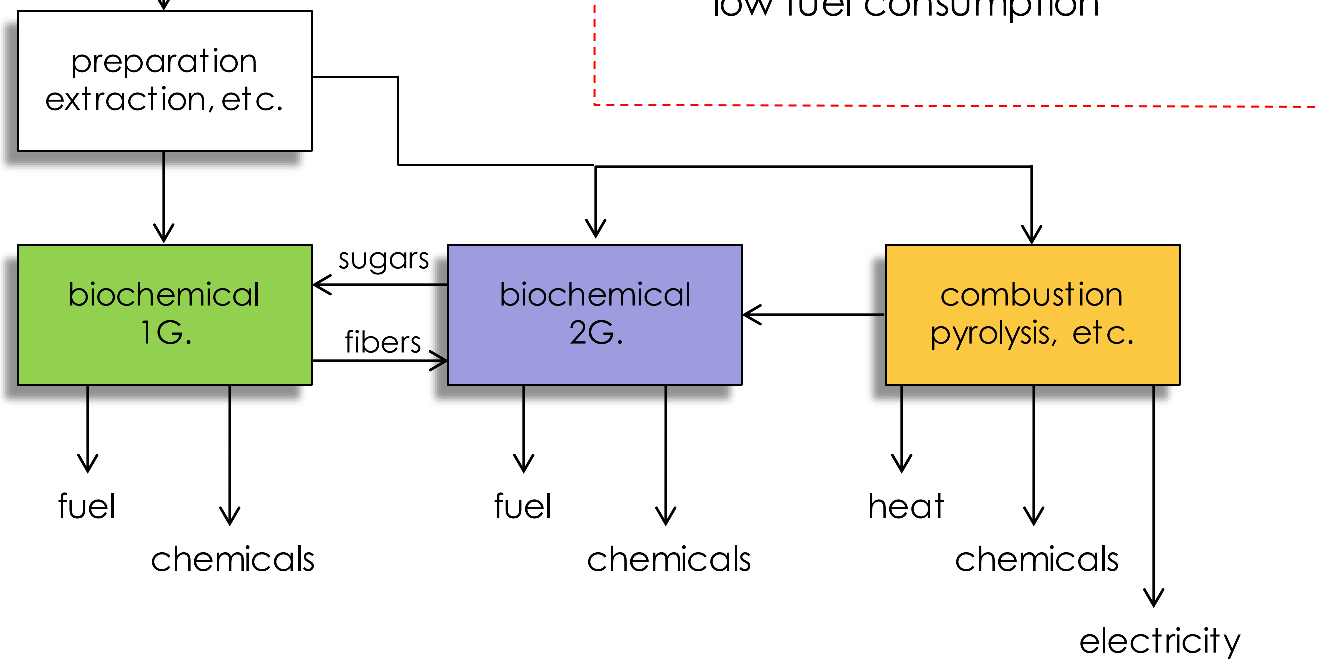
road trains
low soil compaction tires
etc.

Logistics

low fuel consumption

efficient separation
high performance extraction
enzymes production
etc.

Processing



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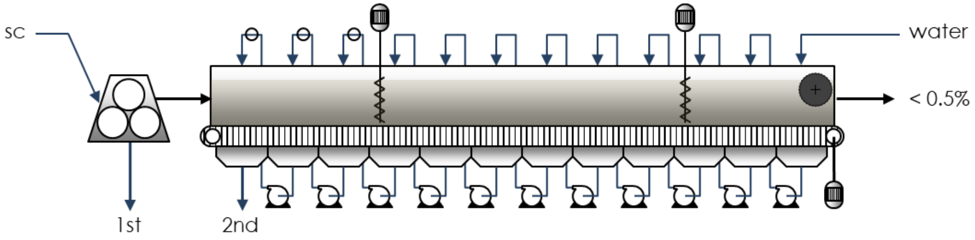


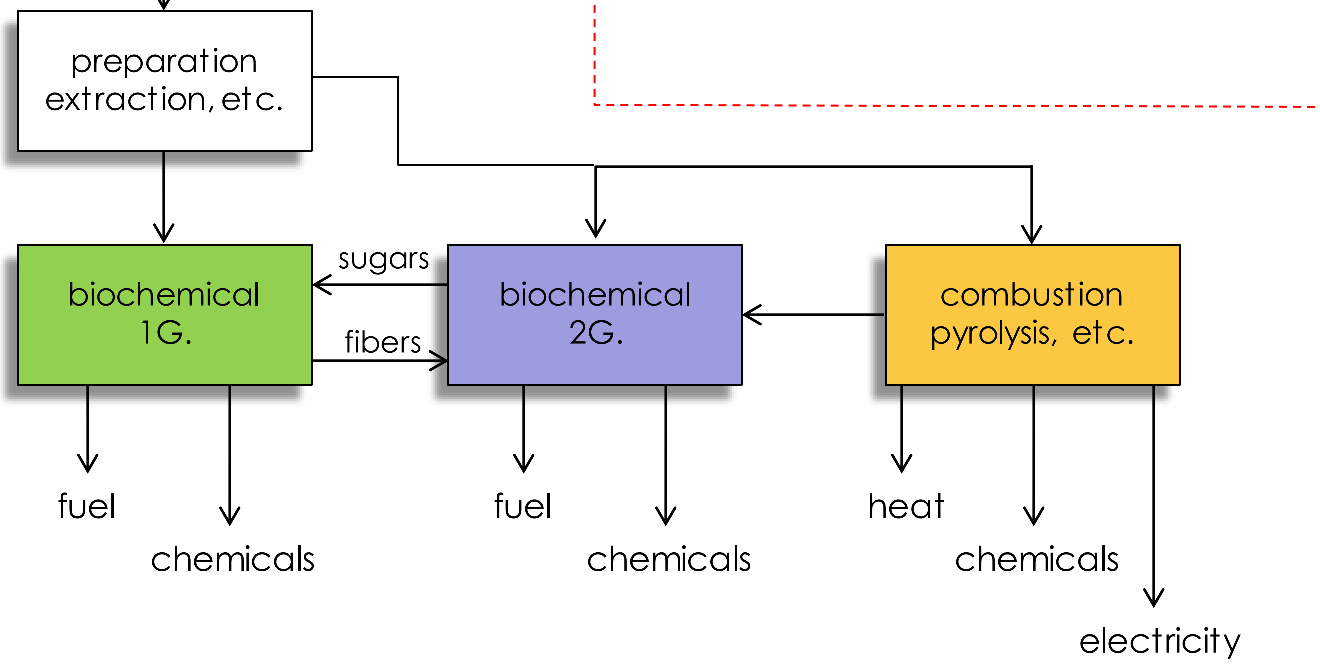
less energy spent on preparation
lower residual sucrose in bagasse
less energy spent on dewatering

road trains
low soil compaction tires
etc.

Logistics

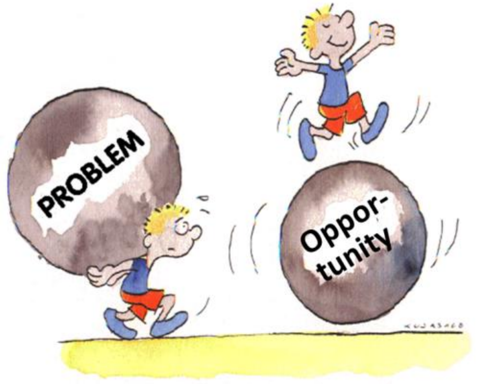
efficient separation
high performance extraction
enzymes production
etc.

Processing



Obstacles and problems are opportunities…

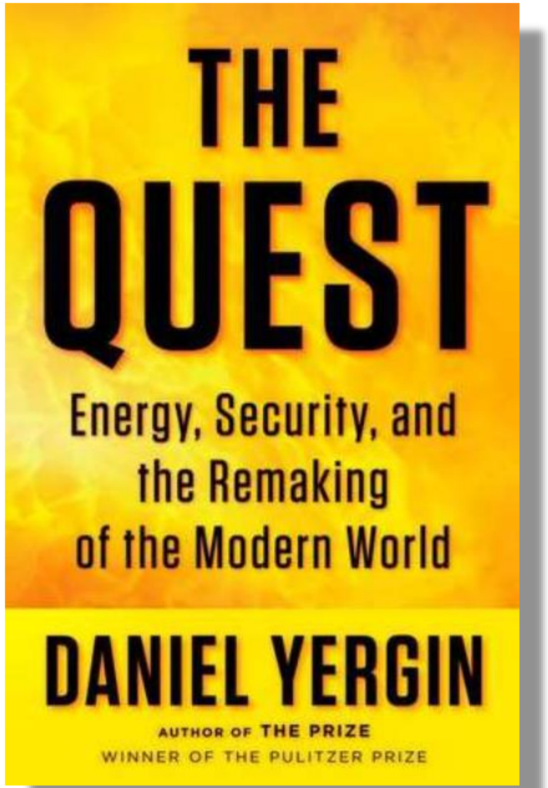
… let’s embrace them !



MUITO OBRIGADO !

Prof. Paulo Seleghim Jr.
USP – São Carlos
seleghim@sc.usp.br

Recommended reading:



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