Thermodynamics and Sustainability

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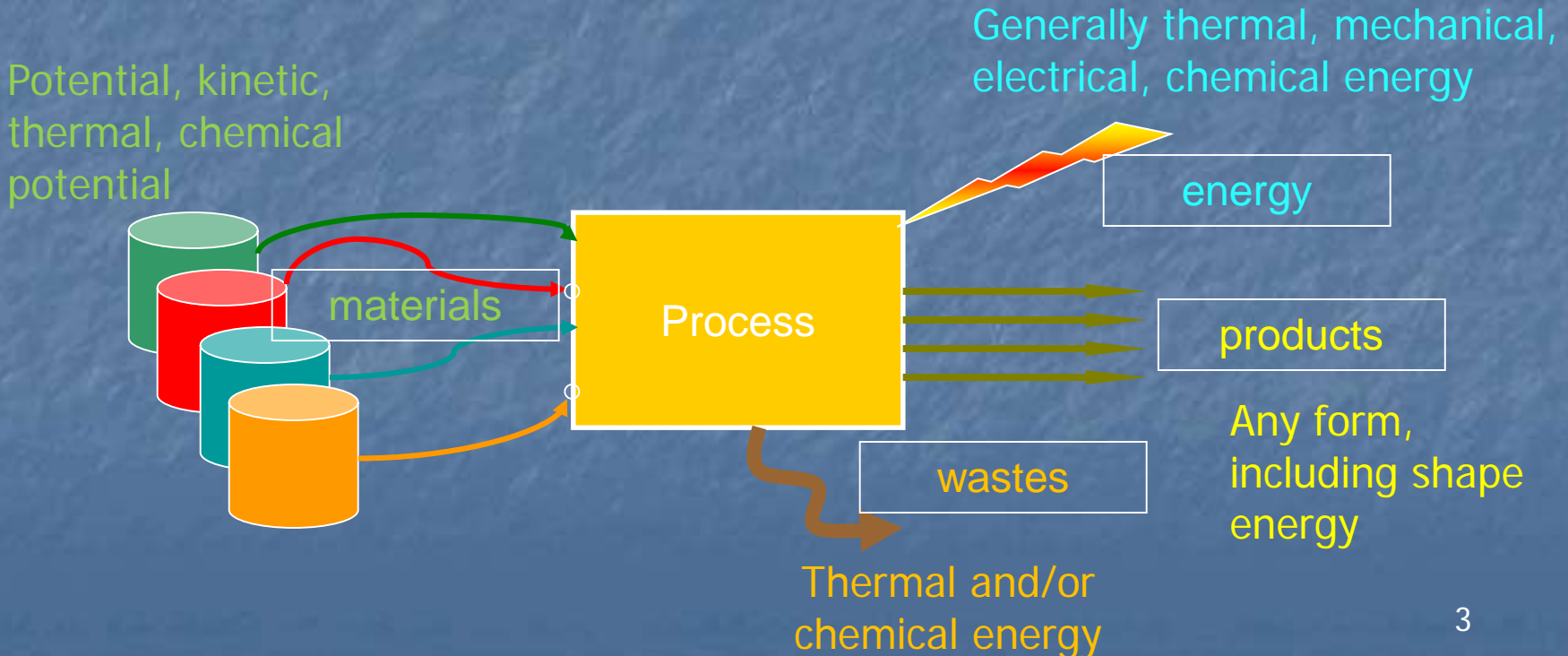
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at Constanta

Outline of the Lectures

1) Basic Engineering Cost Analysis techniques. The "production cost"

2) Limitations of First Law-based accounting methods

3) Exergy: definitions, theoretical background, significant applications

4) Thermo-Economics: origins, development and applications

5) Szargut's Cumulative Exergy Consumption (1961) and Valero's Theory of Exergetic Cost (1986)

6) Thermo-Economic and Exergy analysis of elementary processes

7) Analysis of complex systems: Thermo-Economic and Exergy production cost

8) The Extended Exergy Accounting method and its application to natural and anthropic systems

9) The Exergy Footprint for natural and anthropic systems
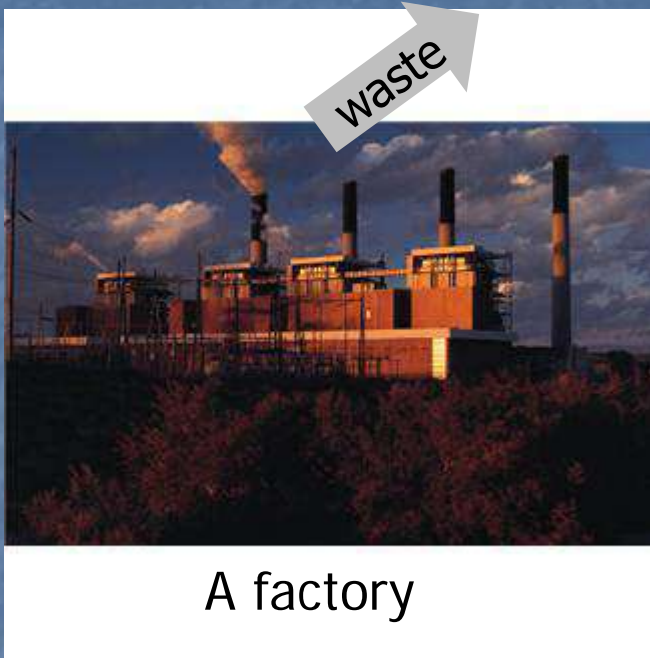
1 - INTRODUCTION

- Energy Conversion Systems

- The concept of "cost"

Although it may seem trivial, I would like to begin by suggesting a very general definition of an "Energy Conversion System"

From the point of view of Thermodynamics, an "Energy Conversion System" is any combination of natural or manufactured devices enacting processes that convert some energy influx into an energy outflux of the same or a different type

Generally thermal, mechanical, electrical, chemical energy

Potential, kinetic, thermal, chemical potential

energy

materials

Process

products

Any form, including shape energy

wastes

Thermal and/or chemical energy

Examples of Energy Conversion Systems - 1

waste

products

materials

energy

A factory

fuel

waste

A Gas Turbine powerplant

electricity
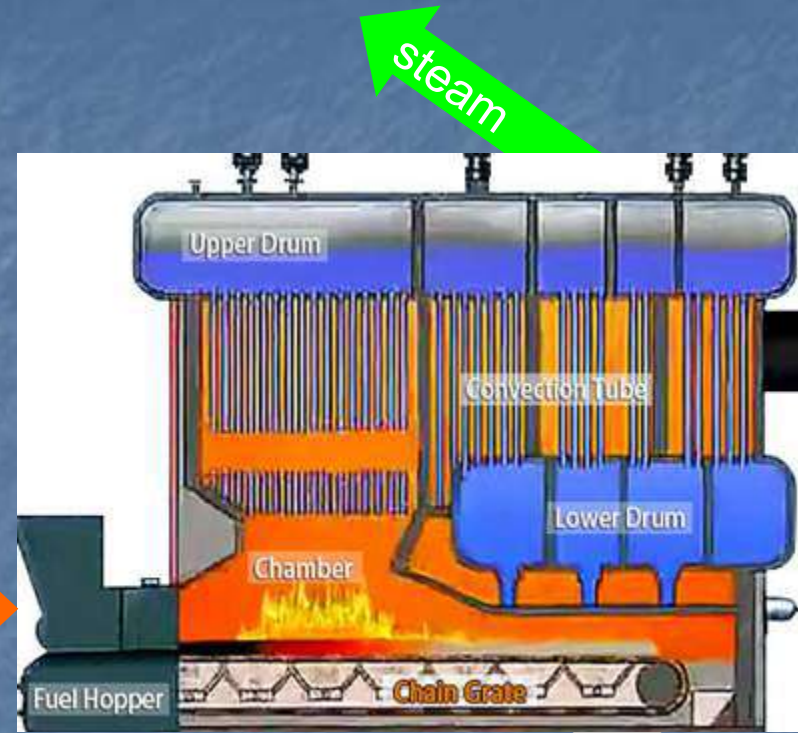
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Examples of Energy Conversion Systems - 2

A Steam Generator

A Heat Exchanger

steam

fuel

waste

heat

fuel

waste

6
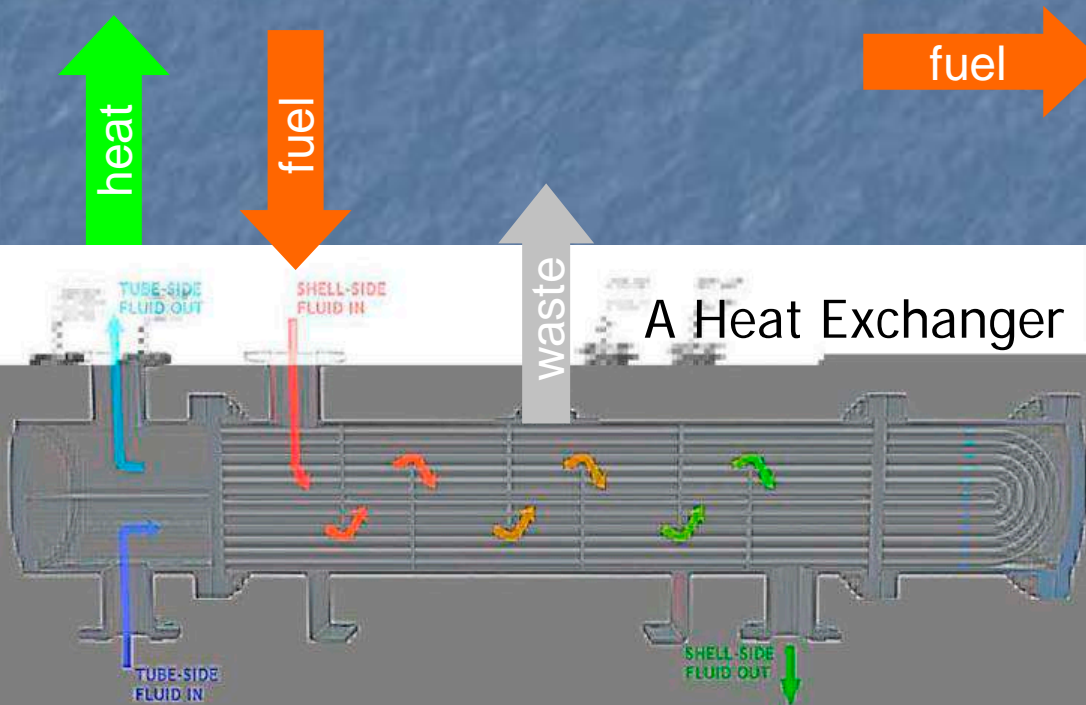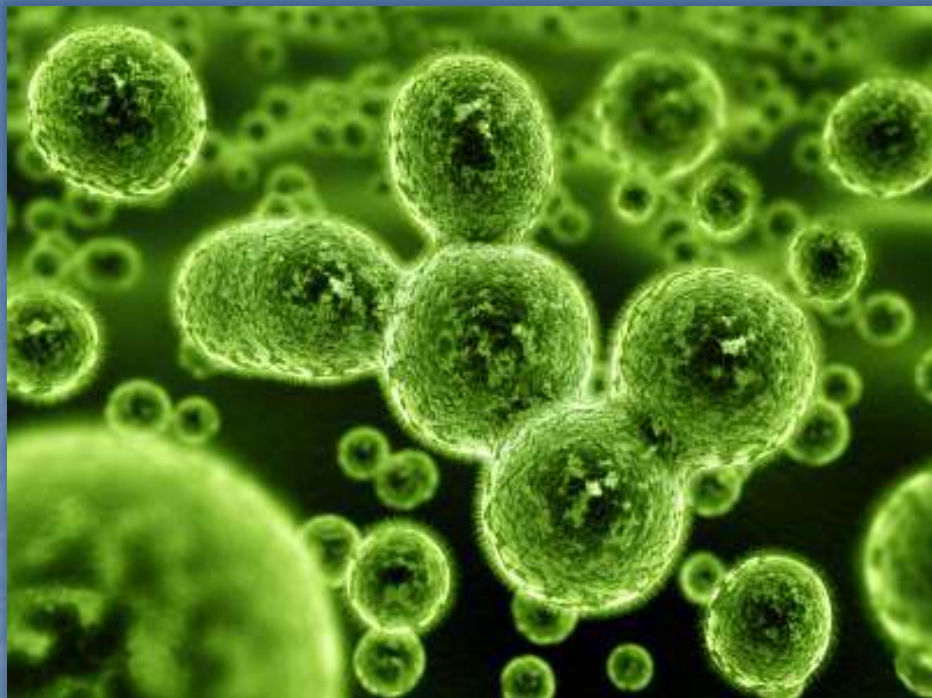
waste

A bacterial colony

energy

matter

survival

energy

survival

A Forest

waste

matter

7

A "Predator + Prey" system

energy

matter

waste

survival

matter

energy
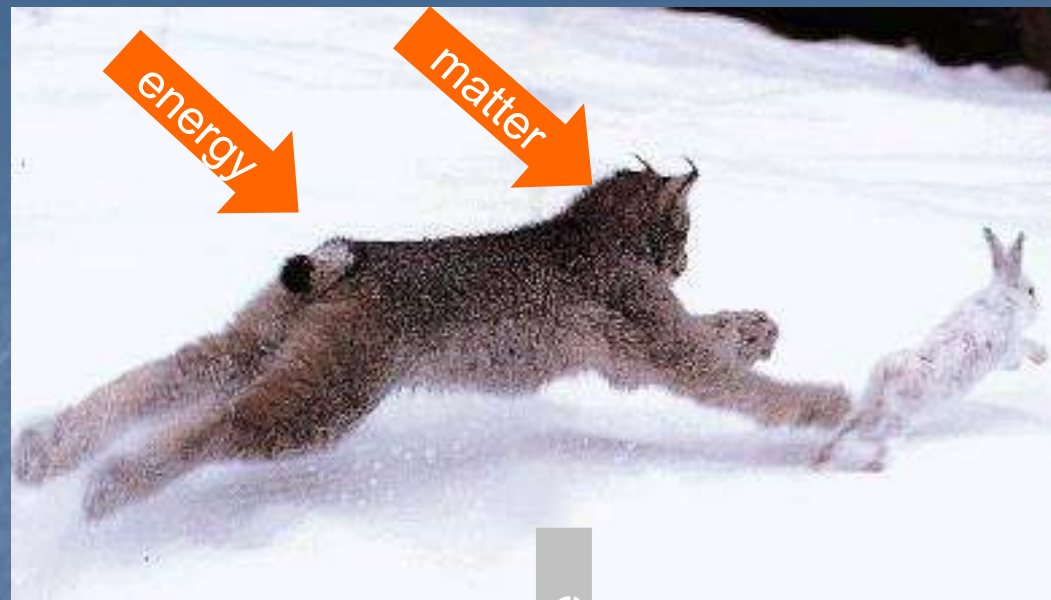
waste
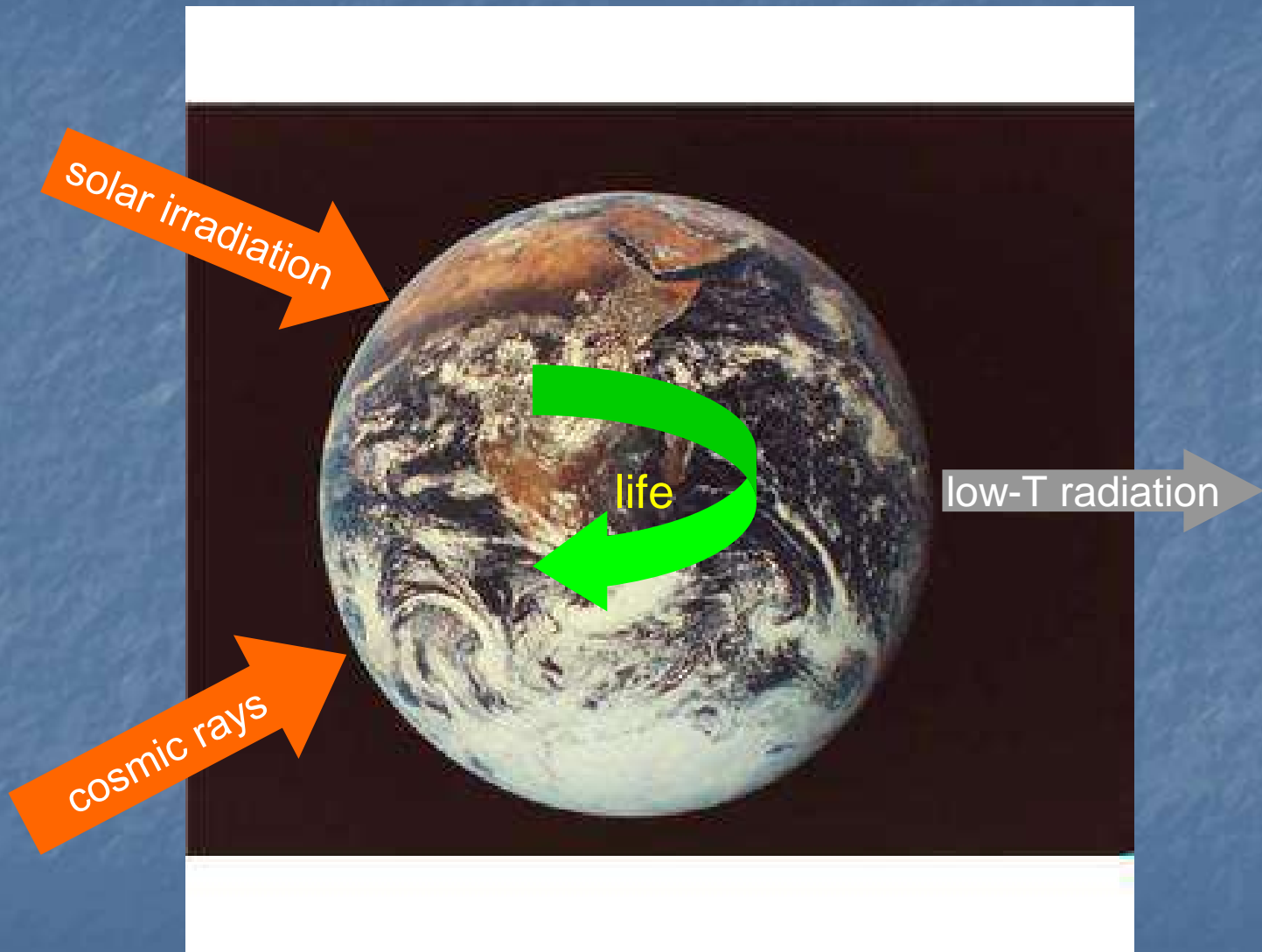
A "Symbiotic" system

survival

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Textbook definitions…

Cost: in economic terms, the amount of money paid to acquire or to produce a commodity (material good or service). In an extended sense, we shall also use this term to indicate the amount of resources needed to produce a commodity. In this second sense, cost can be expressed in non-monetary units.

Price: is equal to the cost augmented by the seller's profit. It depends obviously on the production cost, but it is also substantially influenced by economic factors like demand and offer -or availability and scarcity. It is measured exclusively in proxy (usually, monetary) units. Not a thermodynamic concept.

Value: in Economics, denotes the usefulness of a commodity for either its owner, its producer or its buyer. It is convenient to distinguish (Marx) between *use value* (present value of the commodity for a user who avails himself of it immediately) and *exchange value* (value of a commodity expressed in terms of "units" of value of other commodities). The concept of exchange value can be extended and becomes the *substitution* (or *equivalent*, or *proxy*) value, i.e., the value of a commodity expressed in units of a conventional reference commodity (typically, money)

The practical usefulness of any system, and in particular of Energy Conversion Systems, includes necessarily -with very few and very specific exceptions- the assessment of its "economic feasibility", to ascertain that some properly normalized form of benefit/cost ratio is higher than unity.

In Engineering applications, this "economic feasibility" measures the increase in use (or exchange) value (UV_P) of a product w.r.t. the sum of the use (or exchange) values (UV_F)of all of the commodities necessary for its production.

| Sum of Fuels' use values, C_F →	**Process**	Product use value, C_P →
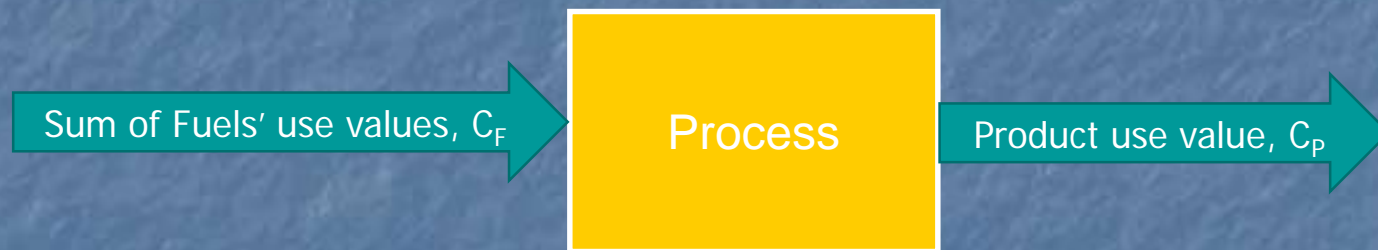
Process is "economically feasible" if $UV_P/UV_F > 1$

A systemic definition of the concept of "cost"

A very general and convenient way to define "cost" is to consider the global balance of a system:

a) Identify the inputs needed to generate the required output: let us define them as "Fuels";

b) Identify the actual outputs, and refer to the desired ones as "Products";

c) Denote the remaining outputs as "Discharges" or "Wastes"

Fuels, F → Process → Products, P (including possible useful "byproducts")

Discharges, D
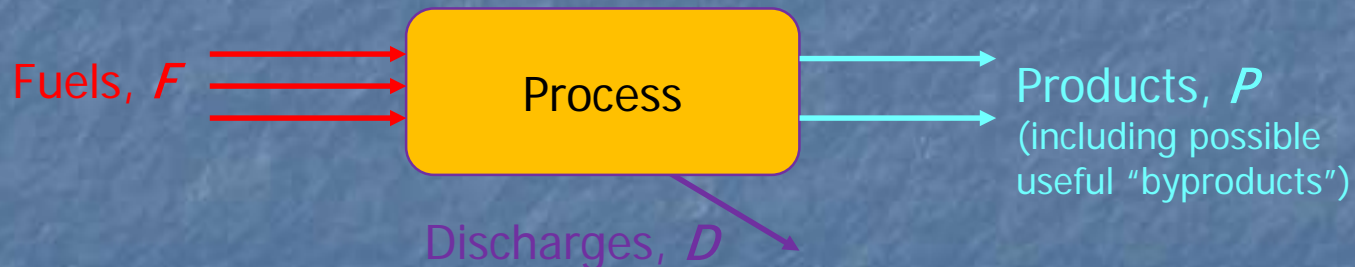
Then: "cost" is defined as $c = F/P$

To perform the "cost analysis" of a system it is necessary to know the structure (and not only the amount) of each component of the cost for the project under evaluation (investment, fuels, operation & maintenance, products, etc.)

A Cost Analysis is a decision support paradigm for the System Designer based on the "cost" of the product(s), usually expressed either in monetary units per product unit (€/piece, €/kg, €/liter, €/kWh...) or in "energy equivalents" (kJ/piece, kJ/kg, kJ/liter, kJ/kWh…)

Fuels, F → [Process] → Products, P (including possible useful "byproducts")

Discharges, D
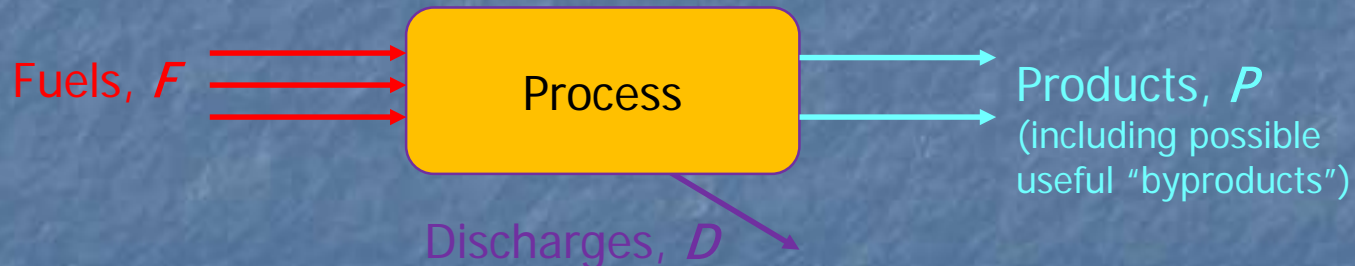
For such a definition to be useful in practice, it is mandatory that *F*, *P* and *D* are expressed in well-defined units. There are several possible choices:
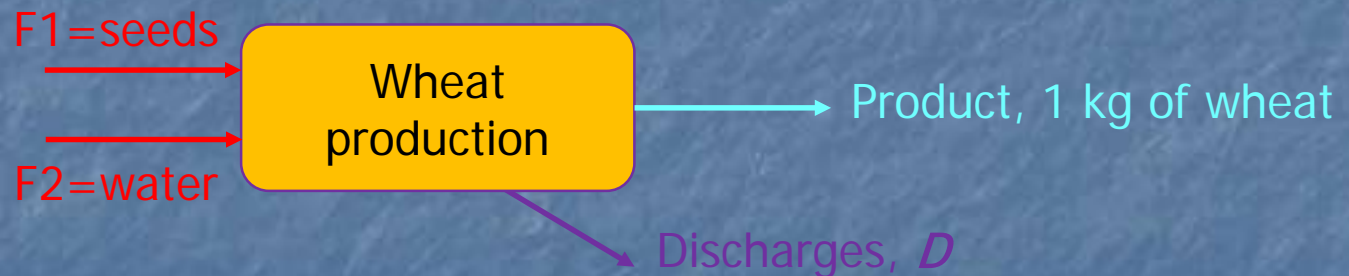
a) Use physical units of the material type, for example "pieces" or "kg".
    Example: to obtain 1 kg of wheat, an average estimate is 12.5 kg of seeds and 1500 kg of water;
b) Use physical units of the immaterial type, for example "J" or "workhours".
    Example: to obtain 1 kg of wheat, an average estimate is 9.3 MJ of energy and 0.065 workhours;
c) Use proxy units expressing both material and immaterial flows, typically (but not necessarily!) monetary.
    Example: to obtain 1 kg of wheat, an average estimate is 0.03 €;
    But also, "1000 kg of wheat are equivalent to 0.1 cow", or "1000 kg of wheat=0.02 ounces of gold"

Costing method (a) was used in ancient times, and is still sometimes used in non-industrialised agricultural contexts

a) Use physical units of the material type, for example "pieces" or "kg". *Example: to obtain 1 kg of wheat, an average estimate is 12.5 kg of seeds and 1500 kg of water;*

In a modern economy this method is "not closed", because it leads to the problem of determining the cost of the different inputs.

How do we independently measure the cost of seeds and water?

F1=seeds

F2=water

Wheat production

Product, 1 kg of wheat

Discharges, D

?

$c=(F1+F2)/P$

Costing method (b) was proposed in the 60'es, when the first concerns about final energy uses were raised. Substantially improved versions are still in use today (Net Energy Analysis, Emergy Analysis, etc.).

b) Use **physical** units of the **immaterial** type, for example "J" or "**workhours**". *Example: to obtain 1 kg of wheat, an average estimate is 9.3 MJ of energy and 0.065 workhours;*

If there are several Fuels, this method leads to the problem of expressing their cost in homogeneous units (how many kJ is 1 workhour worth?)

F1=energy

→ Wheat production → Product, 1 kg of wheat

F2=workhours

Discharges, *D*

?
$c = (F1+F2)/P$
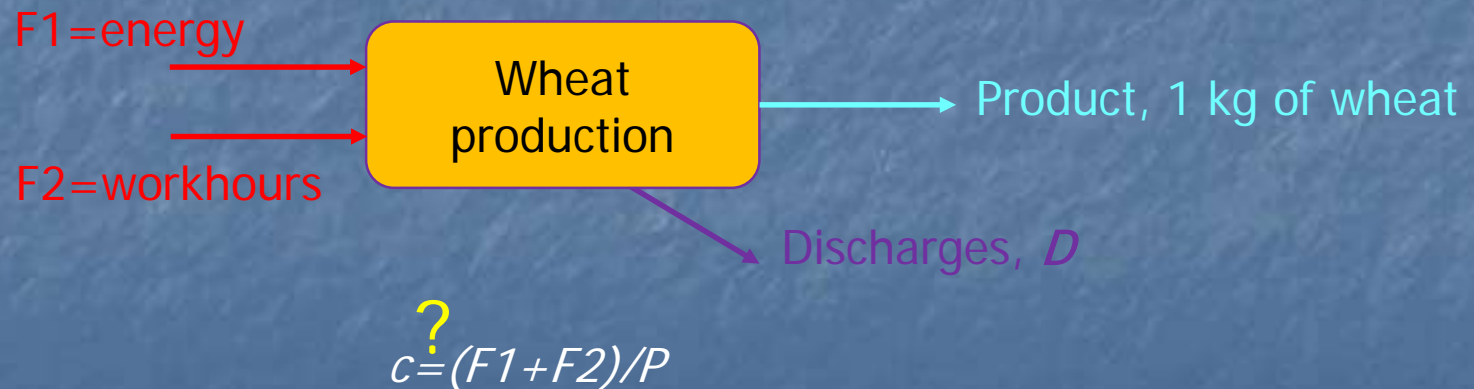
Costing method (c) is the one in common use today.

c) Use proxy units expressing both material and immaterial flows, typically monetary. *Example: to obtain 1 kg of wheat, an average estimate is 0.03 €;*

Not only this method allows to include in *F* the costs of water, workhours, seeds, land use etc., but it also assigns to the Product a proxy (monetary or otherwise) cost that can be carried on to further calculations downstream

F=€ ⟶ **Wheat production** ⟶ Product, 1 kg of wheat

$c=F/P$

Discharges, *D*
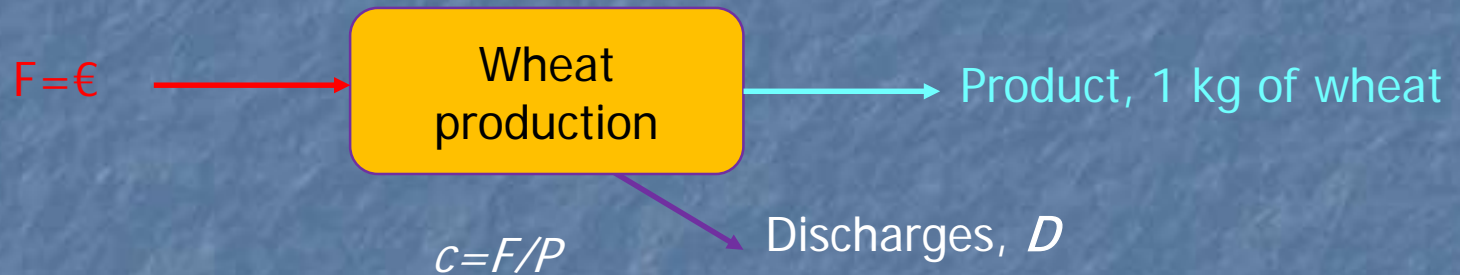
Notice: the method is valid whatever the proxy is!
(kg of gold, kg of silver, carats of diamonds, kg of salt, number of seashells, number of oxydian arrowpoints, hectars of land, number of goats/oxes/horses, number of slaves...)

At the current state of the art, there are several "costing paradigms" that may be classified according to the following criteria:

1) What is the attribute of the Product (and of the Fuels, Wastes and Byproducts) that is being evaluated?
2) What is the costing basis?
3) What is the costing unit?

Costing method	Costing basis (What is "priced")	Economic basis	Cost unit	Examples
Energy Analysis, **EA**	Energy	Physical	kJ/kJ	Embodied Energy 1970, Emergy 1980, Net Energy 1990
Techno-Economics, **EE**	Energy & Materials	Monetary	€/kJ or €/kg	Current Feasibility Studies
Thermo-Economics, **TE, TEC**	Exergy	Monetary	€/kJ	Elsner 1961, El-Sayed 1970, Tsatsaronis 1985, Valero 1986, (Szargut 1967)
Exergy Analysis, **ExA**	Exergy	Physical	kJ/kJ	Rant 1956, Gaggioli 1980, Moran 1982, Szargut 1975, Valero 1986
Extended Exergy Accounting, **EEA**	Primary Exergy	Physical	kJ/kJ	Sciubba 1995 $\Rightarrow$ Exergy Footprint as a sustainability indicator 2019

Energy Analysis, EA

- The costing basis is physical (kJ, kWh);
- The cost is calculated for the unit of energy content of each stream;
- The cost is dimensionless: it measures how many kJ of F are necessary to generate 1 kJ of P;
- The cost is always >1.

e.g., enthalpy values,
kW (=kJ/kg*kg/s)

materials

Process

Energy, kW

products

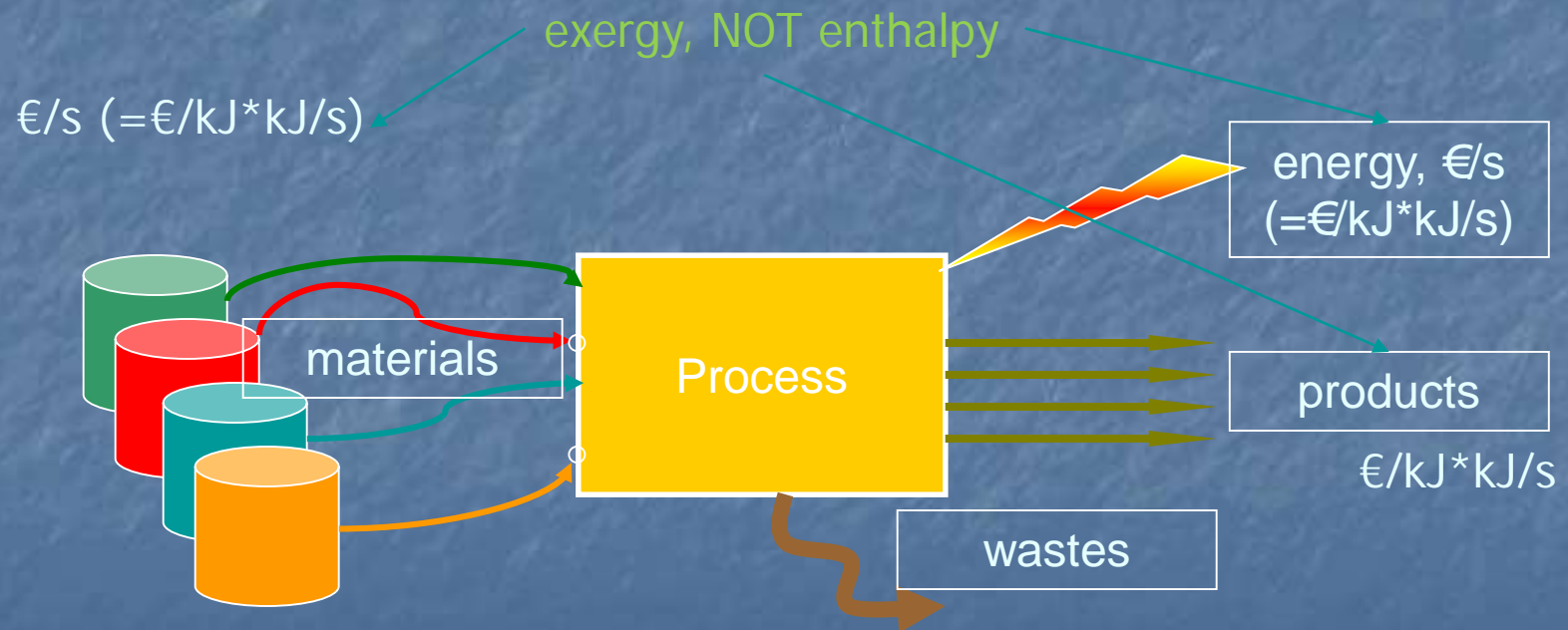enthalpy values,
kW

wastes
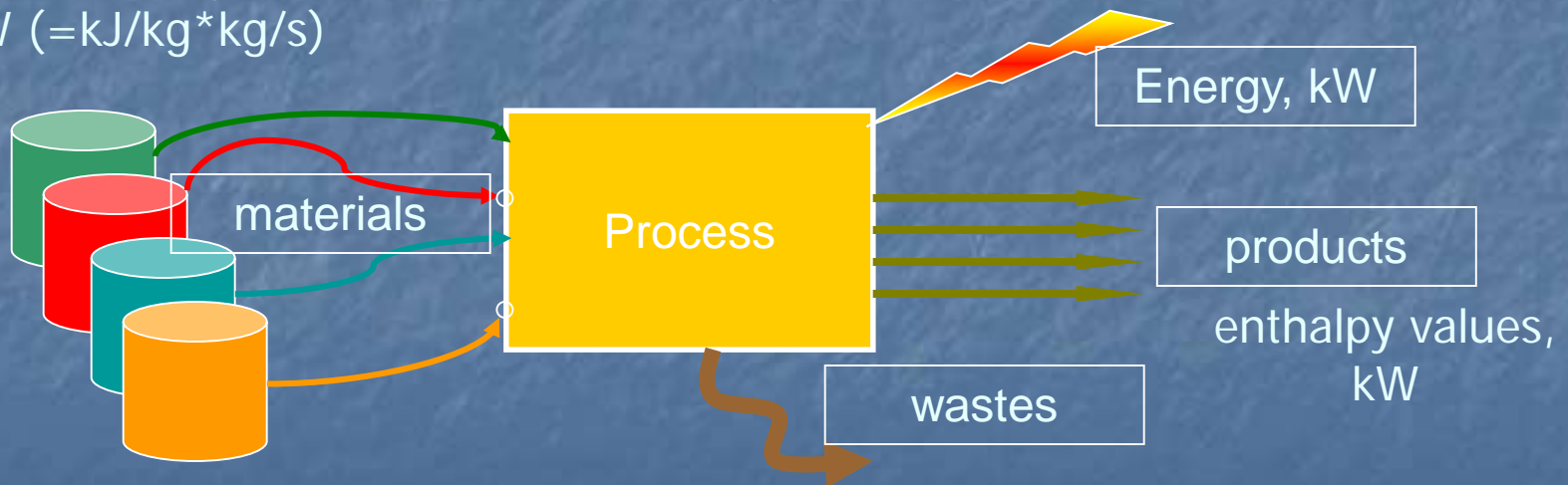
Techno-Economics, EE

- The costing basis is physical (kJ, kg);
- The cost is calculated for the unit of energy content of each immaterial stream and for the unit of mass of each material one;
- The cost is measured in monetary units (proxy) and indicates how many € of *F* are necessary to generate 1 unit of *P*.

€/s (=€/kg*kg/s)

energy,
€/s (=€/kJ*kW)

materials

Process

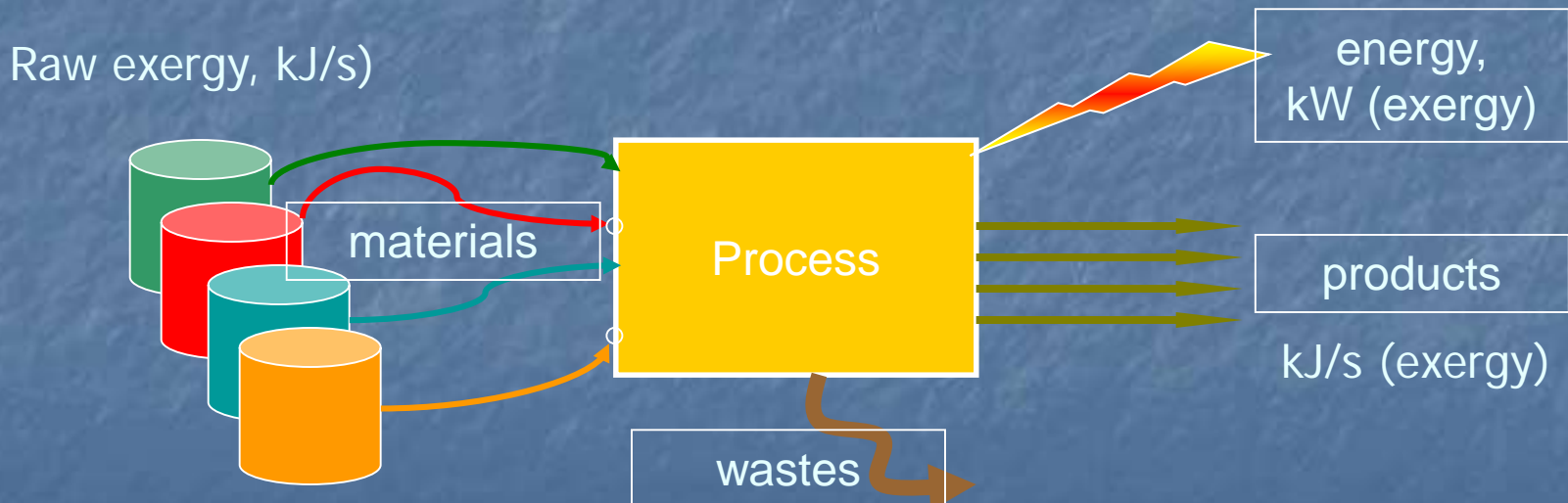products

kg/s; kW

wastes
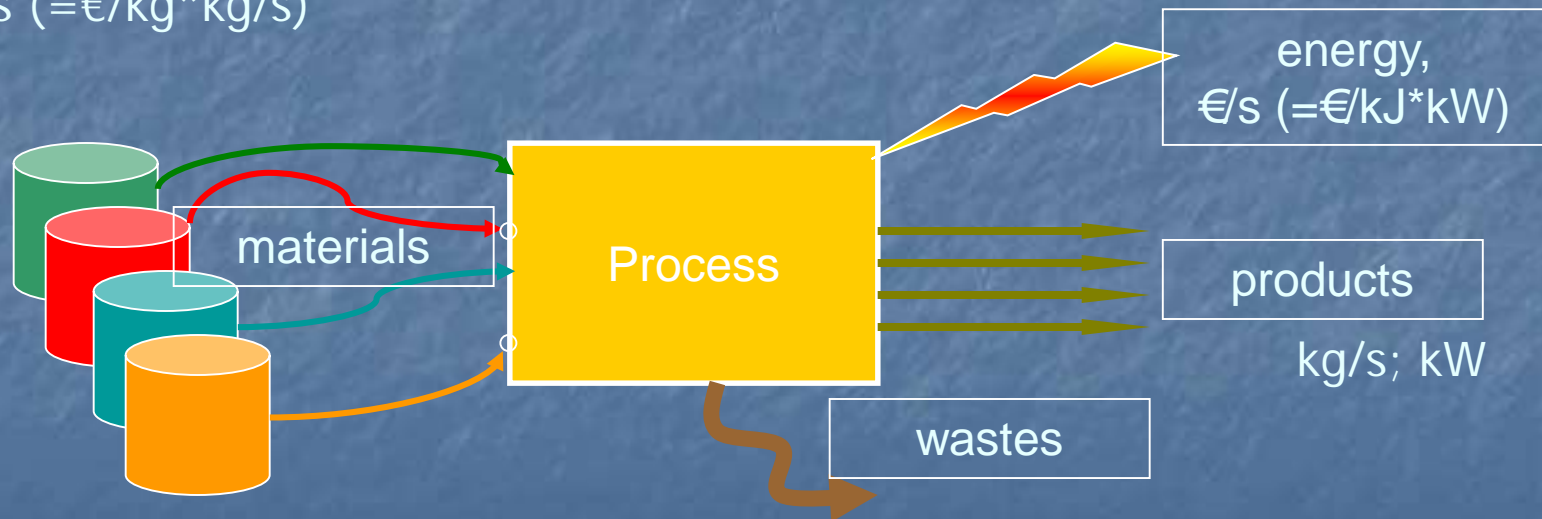
Thermo-Economics, TE

- The costing basis is physical (kJ, kg);
- The cost is calculated for the unit of eXergy content of each stream;
- The cost is measured in monetary units (proxy) and indicates how many € of F are necessary to generate 1 kJ of exergy of P.

exergy, NOT enthalpy

€/s (=€/kJ*kJ/s)

energy, €/s (=€/kJ*kJ/s)

materials

Process

products

€/kJ*kJ/s

wastes

Thermo-Ecological Cost, TEC

- The costing basis is physical (kJ, kg);
- The cost is calculated for the unit of eXergy content of each stream;
- The cost is dimensionless [kJ/kJ] and indicates how many kJ of *F* are necessary to generate 1 kJ of exergy of *P* (original Szargut notation: CExC, Cumulative Exergy Content, kJ)
- Environmental cost is included;
- The cost (cexc, kJ/kJ) is always >1

Raw exergy, kJ/s)

materials

Process

wastes

energy, kW (exergy)

products

kJ/s (exergy)

Exergy Analysis, ExA

- The costing basis is physical (kJ, kWh of exergy);
- The cost is calculated **for the unit of eXergy content** of each stream;
- The cost is dimensionless, since it measures how many exergy kJ of *F* are necessary to generate 1 exergy kJ of *P*;
- The cost is always >1.

exergy, NOT enthalpy

kJ/s (=kJ/kg*kg/s)

materials

Process

energy, €/s kW)

products

kW

wastes
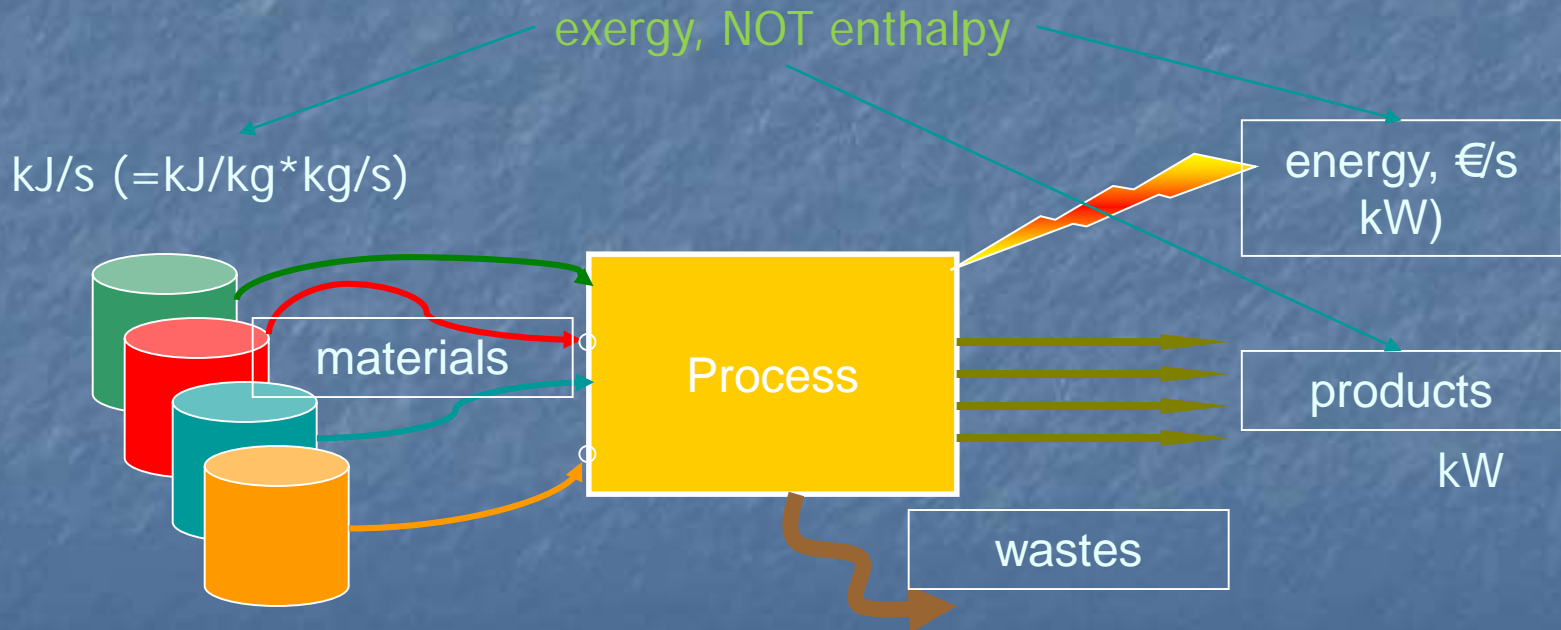
Extended Exergy Accounting, EEA

- The costing basis is physical (kJ, kg);
- The cost is calculated as the equivalent primary eXergy content consumed to generate 1 exergy kJ of each (material or immaterial) stream;
- All Externalities (Labour, Capital, Environmental Damage) are accounted for;
- The cost is dimensionless ($kJ_{primary\ exergy}/kJ_{product}$);
- The cost is >>1.

$kW_{primary\ exergy}$

$kW_{primary\ exergy}$

energy

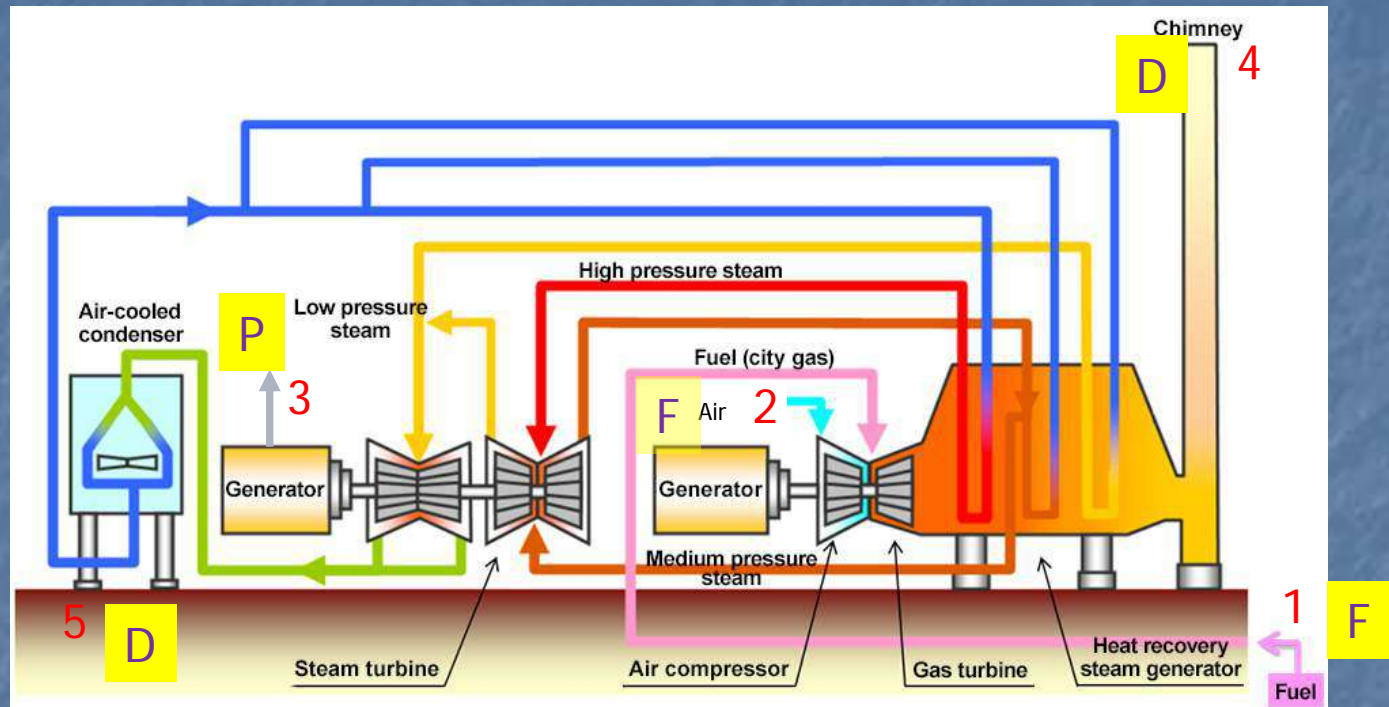materials

Process

products

kW_{exergy}

wastes
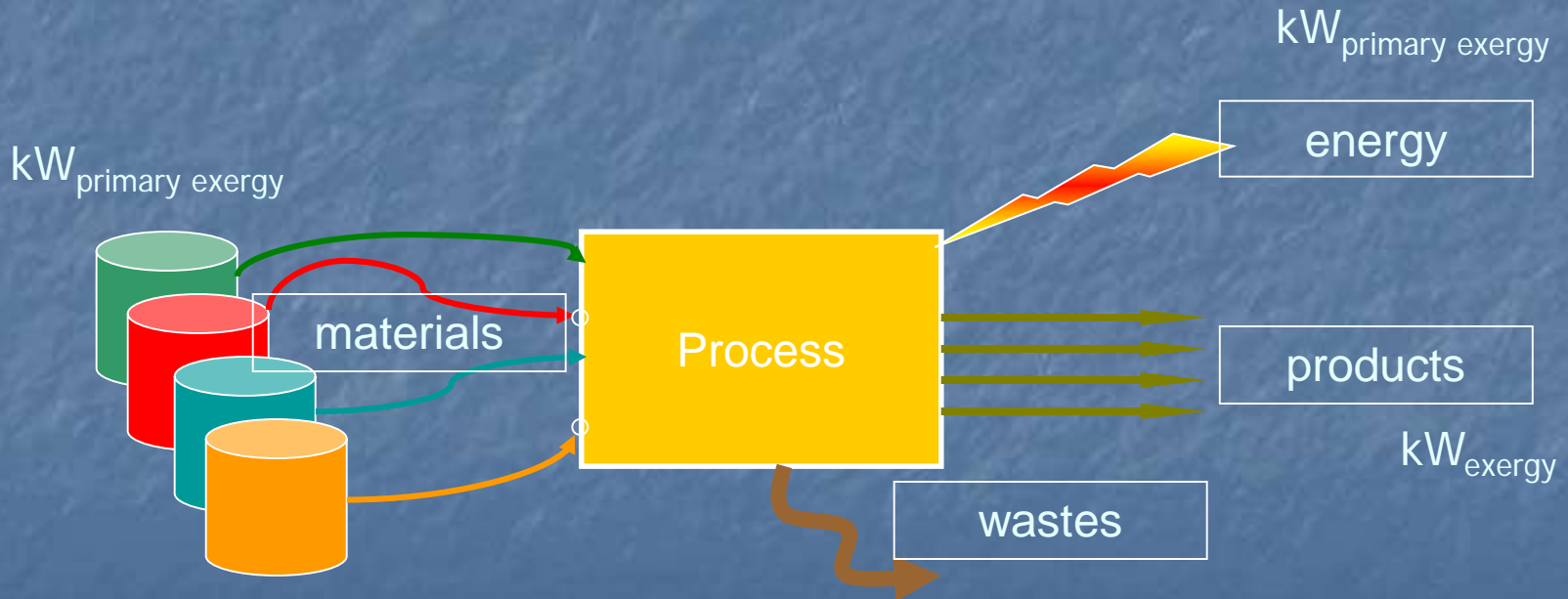
Products and fuels in some common energy conversion systems

Gas Turbine Power Plant
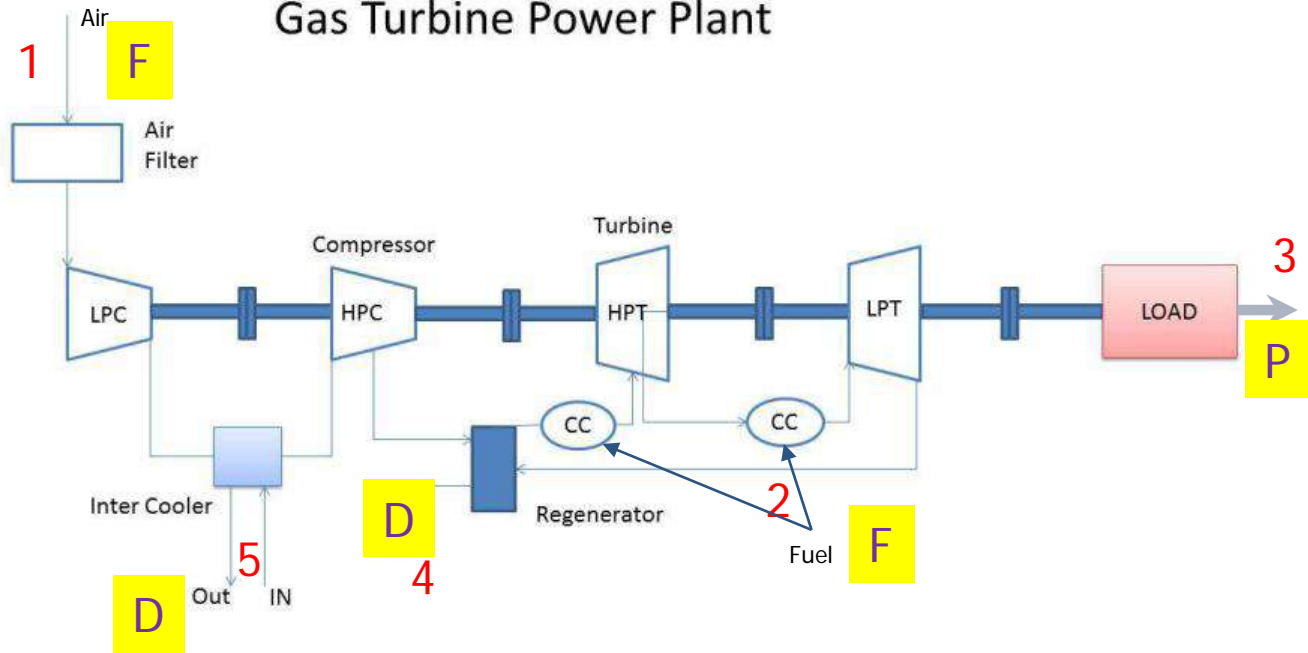
Here, the "product" is clearly electricity (stream #3), the "fuels" are streams #1 and #2 and the "by-products" are hot gas (stream #4) and spent cooling water (stream #5)

# GT-ST Combined Powerplant

Here, the "product" is electricity (stream #3), the "fuels" streams #1 and 2; the "by-products" are hot gas (stream #4) and spent condenser cooling water/air (stream #5)

GT Cogeneration Plant

Simple CHP (Cogeneration) System
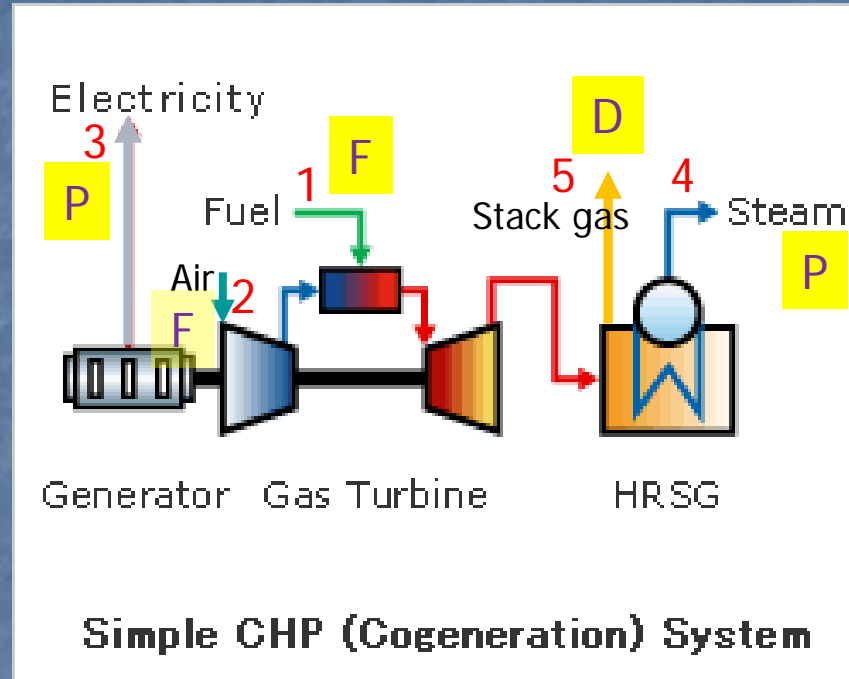
Here, the "products" are electricity (stream #3), and process steam (stream #4), the "fuels" are streams #1 & 2, and the "by-product" is the stack gas (stream #5)

Solar Thermal Plant
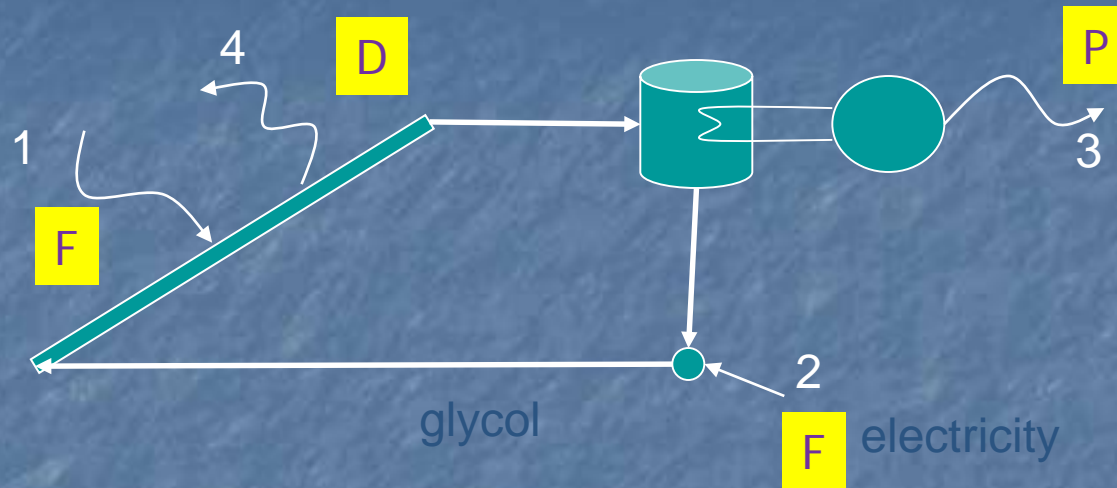
Here, the "product" is heat (stream #3), the "fuels" are solar radiation (stream #1) and electricity (stream #2).The discharge is a thermal energy flow (#4)
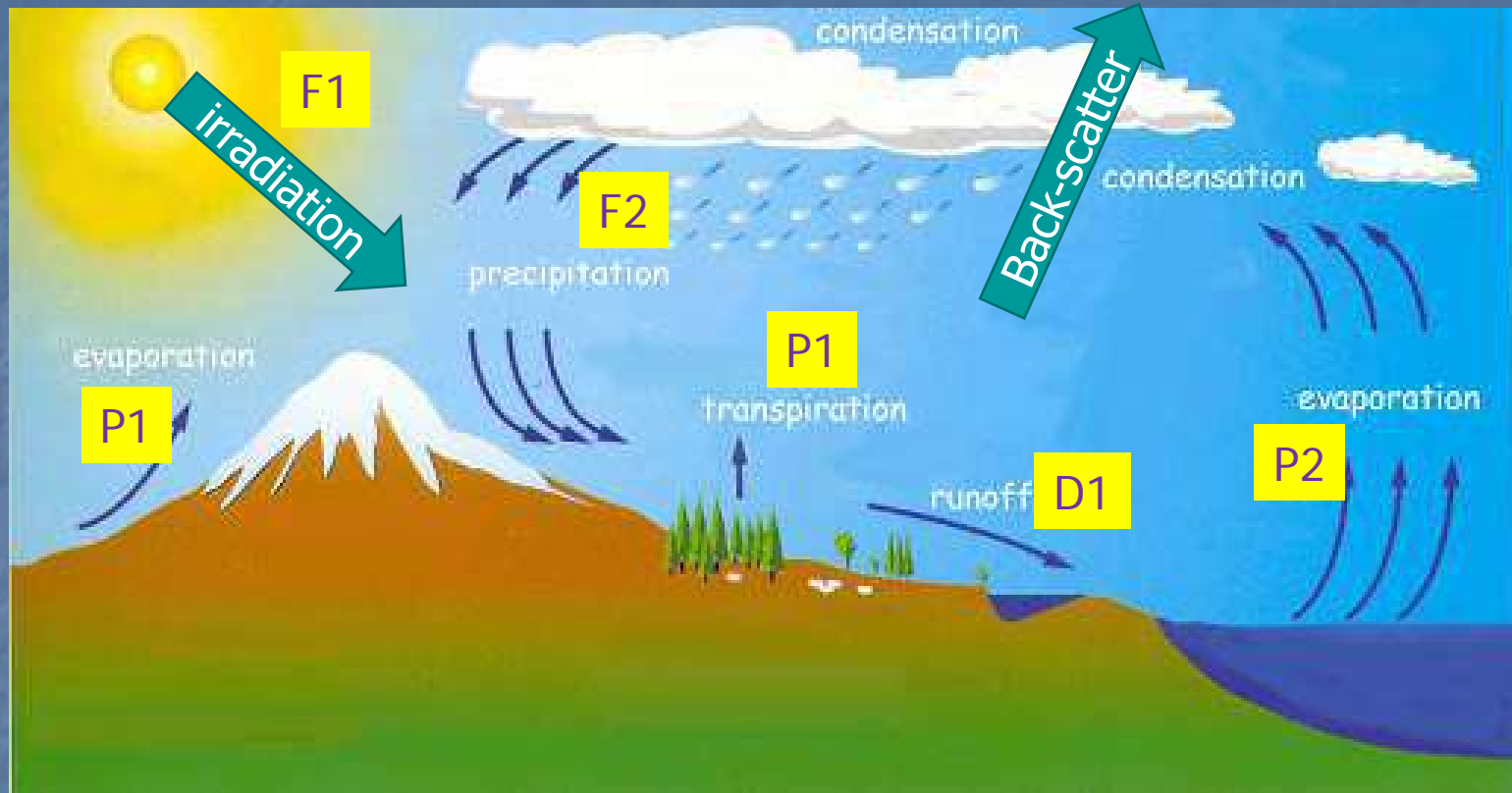
Solar PV with storage
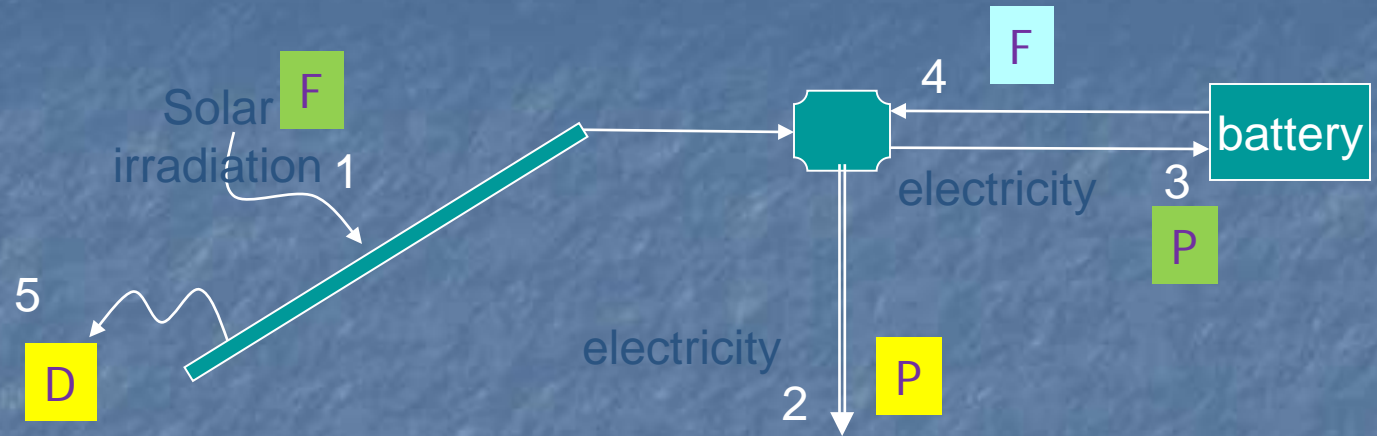
In a PV panel with battery storage, the "products" are electricity to the user (stream #2) and electricity to the battery (stream #3), and the "fuel" is solar radiation (stream #1). The discharge is a thermal energy flow (#5)

At night, the "fuel" is though stream #4, electricity from the battery to the inverter.

Fuels & Products in natural Systems

The "F-P" paradigm can be adapted to natural phenomena: here, the water cycle. F1 directly forces land evaporation and primary transpiration (both "P1" here). The atmospheric circulation (F2) recovers the runoff (D1) and feeds the ocean evaporation (P2).
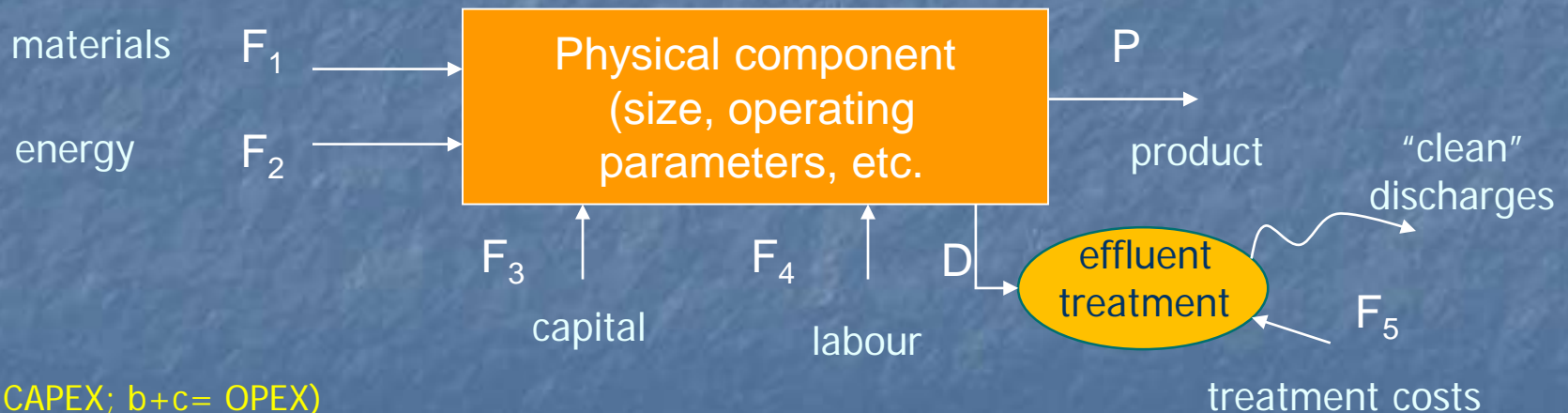
Notice that this model is not unique: another classification would consider F1 as the sole driver of the cycle.

Production factors & Production cost

Limiting for the moment our consideration only to anthropic processes, a complete cost analysis must include not only the fuels and the products, but also some other items that affect the "production cost":

a) Capital costs for the purchase and operation of the equipment;
b) Labour costs (salaries & wages);
c) Operational costs (maintenance, refurbishing, make-up fluids-...);
d) Effluent treatment to reduce or avoid environmental damage.

Items (a), (b), and (d) are collectively called "Externalities".

materials F_1 → **Physical component (size, operating parameters, etc.** → P product "clean" discharges

energy F_2 →

F_3 — capital

F_4 — labour

D — effluent treatment F_5 treatment costs

(a = CAPEX; b+c= OPEX)

Economists have formalised the concept of production cost by identifying 5 **Production Factors**:
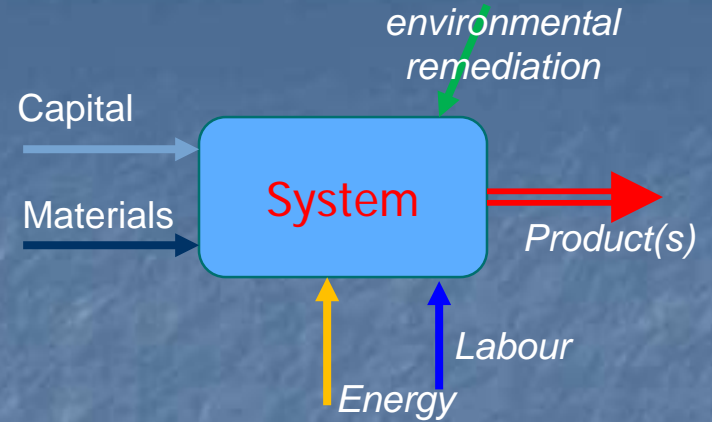
Capital Production Factor $C = f_K * K$
f_K = unit cost of Capital; K = Capital flow (€/s)

Material Production Factor $M = \Sigma(f_{Mi} * m_i)$
f_{Mi} = unit cost of the *i-th* material (€/kg); m_i = *i-th* mass flow rate (kg/s)

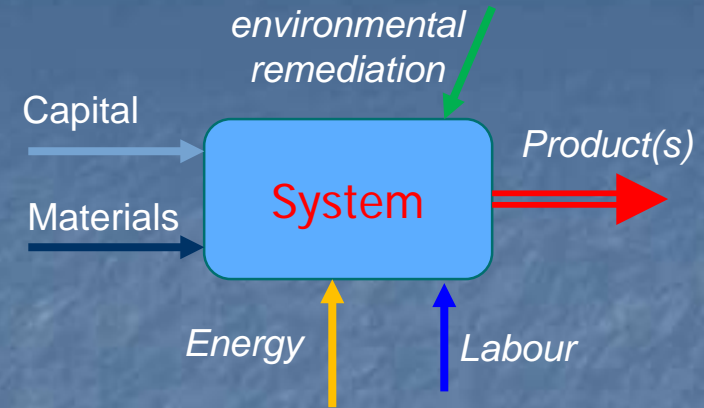**Energy Production Factor** $E = \Sigma(f_{Ek} * h_k)$
f_{Ek} = unit cost of the *k-th* flow (€/J); h_k = energy content (=total enthalpy) of the *k-th* stream (J/s)

Labour Production Factor $L = \Sigma(f_{Lj} * W_j)$
f_{Lj} = unit cost of the *j-th* Labour input (€/workhr; W_j = Labour (workhrs/s)

Environmental "Production Factor" $O = \Sigma(f_{ENVj} C_p * m_p)$
f_{ENVj} = unit environmental cost of the *p-th* effluent (€/kg); m_p = mass flow rate of the *p-th* effluent (kg/s)

Customarily, the production cost of a commodity is thus expressed by a "Production Function" Φ whose operands are the products of the unit costs of each production factor by an extensive measure of the factor itself (J for energy, kg for materials, € for capital and environmental cost, work-hours for Labour):

$$c_j = f(C, M, E, L, O)$$

In more rigorous mathematical terms, we can say that the production cost of the output of any component or unit is a function of the cost of the inputs and of that of the component itself.

But, since the amount of output depends -for the same input- on the efficiency of the component, and since both F_i and η_i are in turn functions of the process thermodynamic parameters x_j, of the material properties π_κ, of the hardware design variables d_i and of the allocation criteria a_m (each suffix varies in its proper range), the cost function Φ can be formally rewritten as

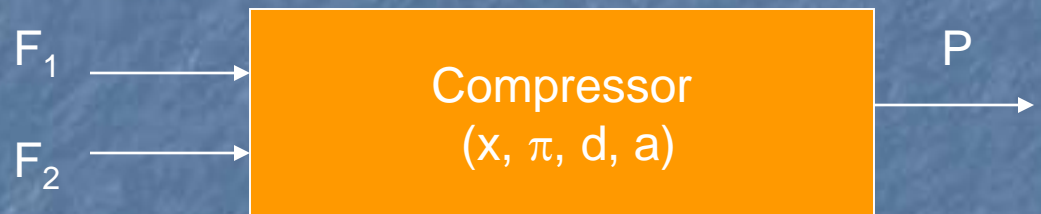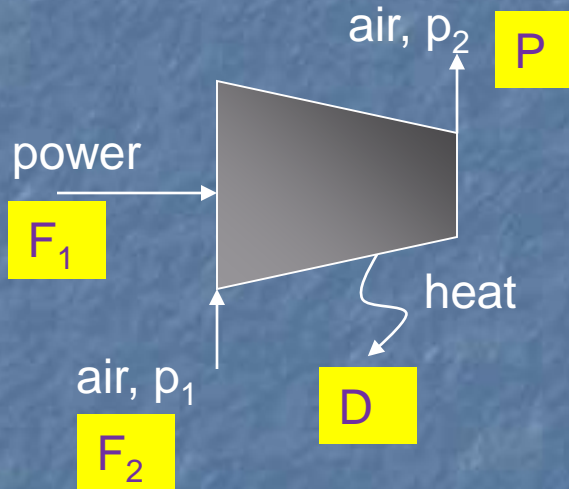$$C_{products} = \Phi(x_i, \pi_\kappa, d_i, a_m) * C_{inputs}$$
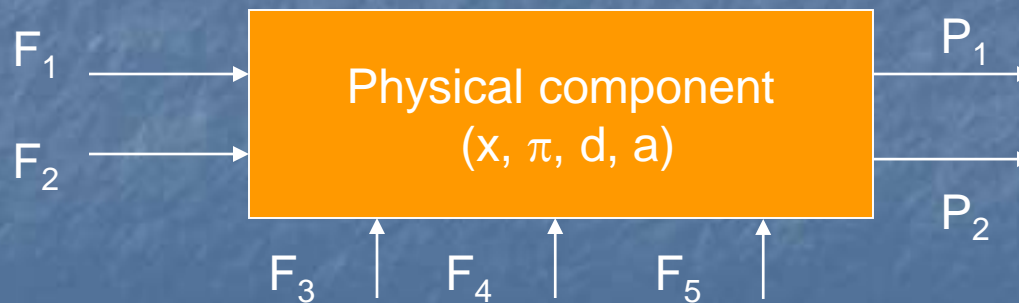
Example: Gas Compressor

E_{i1}=air; E_{i2}=shaft power; E_{o1}=compressed air;
x_j= $\langle m_{air}, p_{in}, p_{out}, T_{in}, T_{out}\rangle$; π_k= $\langle R_{air}, c_{p,air},$ steel, shaft…$\rangle$; d_i = $\langle D_1, D_2, N_{stages}…\rangle$

$$C_P=\Phi(x_j,\pi_k,d_i)*C(F_1,F_2)$$

air, p_2 | P |

power

| F_1 |

heat

air, p_1

| D |

| F_2 |

F_1

F_2

Compressor
(x, π, d, a)

P

More recently, it has been shown that it is possible to construct a physical costing paradigm in which the energy, material and Environmental cost-related "Production Factors" are represented solely in terms of exergy.

It is clear that once the three factors E, M and O, which are *per se* incommensurable with each other, are made homogeneous by adopting exergy as the common quantifier for all streams that flow "in" and "out of" the process, the irreversibilities in the production chain are better accounted for: this is the basis of the **Extended Exergy Accounting**. There is no problem in expressing Energy- and Material inputs and outputs in terms of exergy: how to assign a proper exergy cost to Environmental effects is still the topic of some fundamental debate and shall be discussed in Chapter 9.

Questions & Answers time!