



Skills for Sustainability



Manufacturing Skills Australia

About mass and energy balancing

CO₂ 5Y SF₆ 4M °C
kW.h Kg NO_x
kL \$ CH₄ % MJ GWP

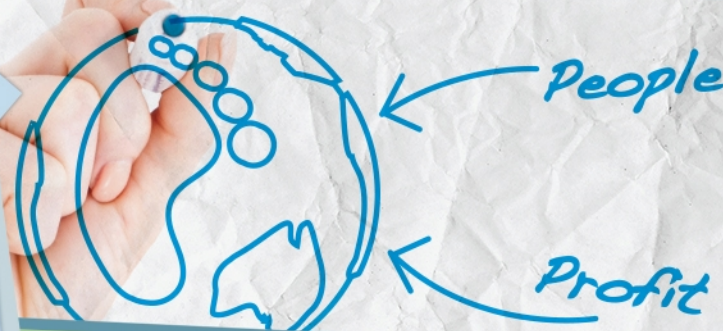


This project is supported by the Australian Government
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About mass and energy balancing

This guide provides general information about mass and energy balancing. It explains the basic concepts and demonstrates that a range of options might be relevant, depending on the context.

The information is relevant to several units of competency in the MSS11 Sustainability Training Package, however, the guide is **not** aligned to a specific unit of competency or AQF level.

What is mass and energy balancing?

Mass balances (also known as material balances) and energy balances are calculation techniques to allow you to calculate the amount of mass (or energy) in process and waste streams. It is typically used where it is difficult to measure directly.

Principle

Mass and energy balances are based on the first law of thermodynamics.

	Formal definition	Colloquial version
First law	Mass and energy cannot be created or destroyed ¹	You can't win!
Second law	Entropy ² will spontaneously increase to reach an equilibrium	You can't break even!
Third law	Entropy is only zero at absolute zero (-273.15 °C)	You can't get out of the game!

So, by applying the first law, anything which goes into a system (or process step) must come out or be stored in it.

¹ For convenience we ignore nuclear reactions where mass is converted into energy.

² Entropy is most easily thought of as 'the degree of disorder' which will spontaneously increase unless we exert work. .



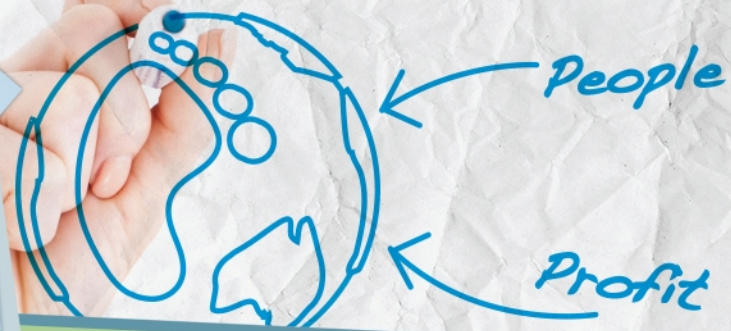
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kL

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NO_x



Technique

The basic calculation is simple – what goes in must come out, unless it is stored in the system, i.e.

Streams IN = Streams OUT

Balances where we have changes in the nature of the streams entering and leaving (e.g. materials might change through chemical reactions or energy might change from electricity to heat or motion) are more complex as we first need to work out the relationship between the changes in the streams.

Also, the more streams we have and the more unknowns we have the more complex the maths becomes. So, Keep It Short and Simple (KISS) where possible.

Mass and energy balancing may be applied over an entire organisation, plant or factory, over an individual process step or item of plant/equipment, or anything in between. It is simpler to choose a 'process chunk' where more data is available or is easily measured or otherwise obtained.

Vast volumes have been written on mass and energy balancing and they will not be reproduced here. The basics are:

1. Decide the boundaries of the process to be analysed so that it is:
 - relevant to what you want to know
 - feasible to obtain/measure the required data
2. Determine the mass/mass flow rate of all materials/streams entering (or energy entering the process).
3. Determine the mass/mass flow rate, of all materials/streams leaving (or energy leaving the process).
4. Identify 'streams' for which you do not have the mass or energy values.
5. Use the mass/energy balancing techniques demonstrated above to calculate the missing numbers.



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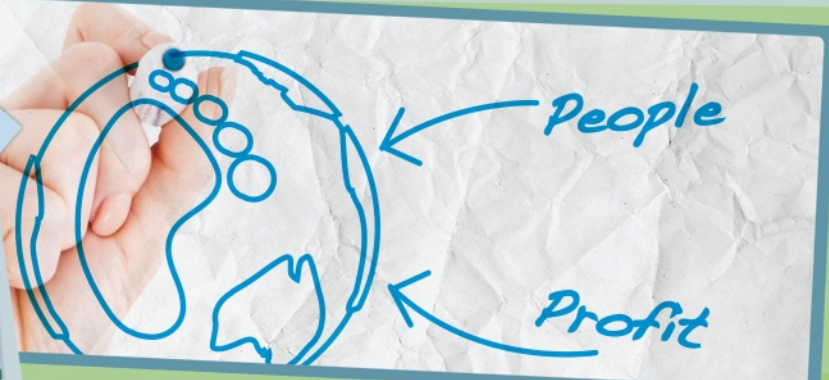
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A few key points to remember:

- mass balancing should be done in mass (kg) – not volume, although if there is no change in density volume will work OK (to convert volume to mass, multiply volume by density) and some preliminary calculations may be needed to convert mass into kg
- energy balancing should be done in Joules (J), and a few preliminary calculation may need to be done to convert energy into J
- it doesn't matter whether the calculation is done in mass or mass flow rate, but the use of mass or mass flow rate must be consistent for all streams
- the fewer streams and materials included, the easier the calculation.

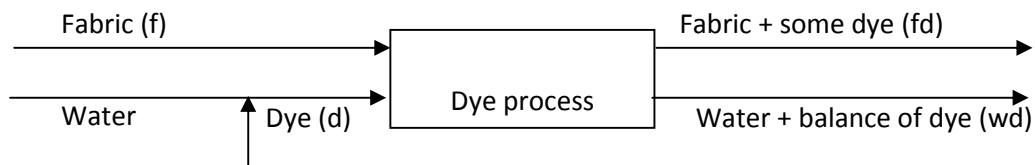
Some examples

Dye loss

A company is dyeing fabric. They measure the dry substance weight of the fabric before it is dyed. They then measure the dry substance weight of the fabric after it is dyed and all fixing salts, and so on, have been washed out. The difference is the amount of dye absorbed by the fabric. If they then compare this with the amount of dye in the dye solution, this difference represents the amount of dye sent to trade waste from the process.

This indirect method of determining dye waste can be easier than trying to measure dye in the wastewater which will be fairly dilute.

Representing this diagrammatically:



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Representing this mathematically: $f + d = fd + wd$

[e.g. $1 \text{ kg} + 0.05 \text{ kg} = 1.03 \text{ kg} + wd$]

Note that we have ignored the water which passes through the process and as we are working on dry fabric weights doesn't change our outcome.

So, dye to waste (wd) is: $wd = d - (fd - f)$

[e.g. $wd = 0.05 - (1.03 - 1)$]

$= 0.02 \text{ kg}$

or percent dye to waste: $= (wd/d) \times 100$

$= [\text{e.g. } (0.02/0.05) \times 100 = 40\%]$

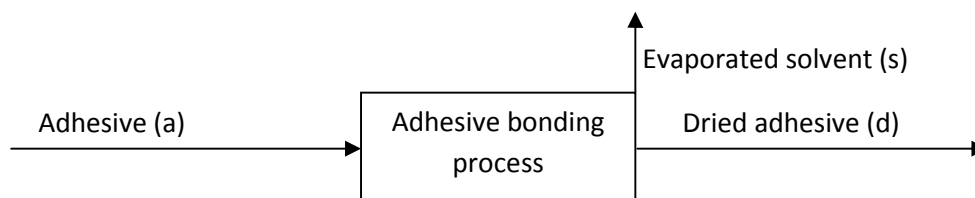
This percentage can then be used to estimate total dye being sent to waste once we know the mass of dye being fed to the process.

Solvent loss

A furnishing company is using a solvent-based adhesive for part of their process. They would like to know how much solvent they are emitting and the possible greenhouse gas (GHG) equivalent.

They apply an amount of adhesive to a sample substrate and weigh it. They then allow it to dry in a similar manner to what it would during production and weigh it again. (Note that to keep it simple we should use a substrate which will not change weight during the drying process).

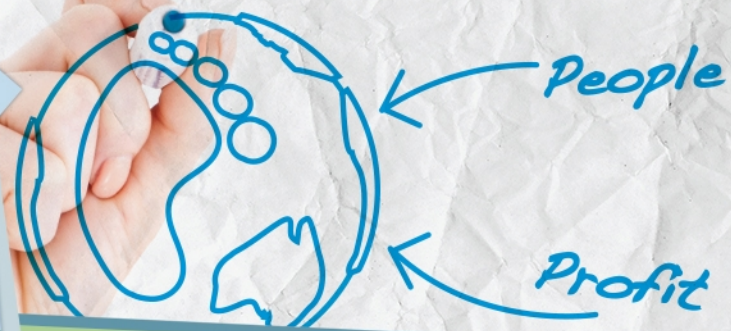
Diagrammatically the process is:



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Representing this mathematically:

$$a = d + s$$

$$[\text{e.g. } 1 \text{ kg} = 0.18 \text{ kg} + s]$$

So, solvent emission is:

$$s = a - d$$

$$[\text{e.g. } s = 1 - 0.18]$$

$$s = 0.82 \text{ kg}$$

or percentage solvent emission

$$= (s/a) \times 100$$

$$[\text{e.g. } (0.82/1) \times 100 = 82\%]$$

This percentage can then be used to estimate total solvent emissions once we know the mass of adhesive being used.

If we wish to then calculate equivalent tonnes of carbon dioxide (CO₂) we:

- identify what chemical the solvent is (read the label, look up the material safety data sheets (MSDS))
- multiply the tonnes of solvent by the global warming potential (GWP) factor to determine equivalent tonnes of CO₂.

Chemical reaction

We frequently use chemical reactions. Combustion is the most common.

A company is using natural gas to heat part of its process. Here, the chemical nature of the mass changes as a result of the chemical process, but it is not destroyed. We first need to write, or look up, the balanced chemical equation for the combustion of natural gas. For convenience natural gas may be assumed to be methane (CH₄). It may also contain some ethane (C₂H₆) and some inerts which won't burn. Unless we need great accuracy we can ignore these.



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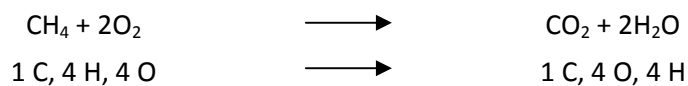
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Remember, mass can neither be created nor destroyed, so we must have the same number of atoms of each element on each side of the equation.



If we now work out/look up the molecular weight of each molecule in this equation, we will also find that the total mass on each side of the equation is also the same:

$$\begin{array}{ccc} 16 + 2 \times 32 & \longrightarrow & 44 + 2 \times 18 \\ 16 + 64 & \longrightarrow & 44 + 36 \\ 80 & \longrightarrow & 80 \end{array}$$

So, for every 16 tonnes of CH_4 consumed, 44 tonnes of CO_2 is produced and 36 tonnes of water. While water does have a GWP, it is not currently considered a problem as it does not persist in the atmosphere, falling out as rain, mist, and so on.

The tea kettle

How much heat is wasted by boiling a kettle? This can be determined by a simple energy balance.

The diagrammatic representation is:



Energy balancing still applies the first law of thermodynamics, but as energy changes form so easily, and we use it in many different forms, we need to do a few sums before we start.

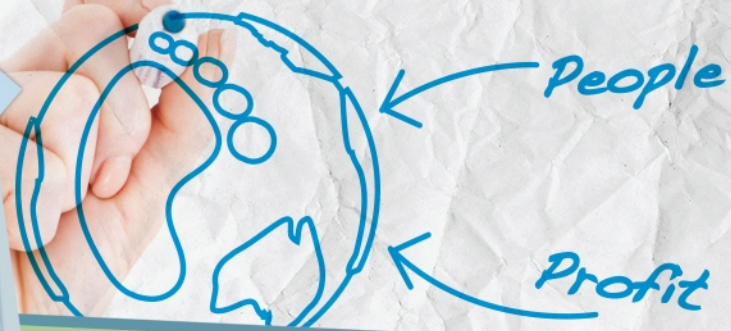
Electricity consumed is determined from the rating plate on the kettle and the time it takes to boil the water. A 2200 W (look up the rating plate) kettle takes 200 seconds to boil 1 L (to keep the maths simple) of water. Fortunately, as the density of water is 1000 kg.m^{-3} , 1 L water weighs 1 kg.



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The water is heated from 20 °C to 100 °C. We will assume minimum evaporation to simplify the maths. To calculate the heat consumed, we need the specific heat capacity of water (i.e. the heat required to raise its temperature by one degree = 4.187 kJ.kg⁻¹.K⁻¹).

Heat in: = watts x seconds

$$= 2\,200 \times 200$$

$$= 440\,000 \text{ J}$$

Heat used by water: = mcΔT³

$$= 1 \times 4187 \times (100 - 20)$$

$$= 334\,960 \text{ J}$$

So energy balance:

Heat in = heat used + heat wasted

$$440\,000 = 334\,960 + \text{heat wasted}$$

Heat wasted = 440 000 – 334 960

$$= 105\,040 \text{ J}$$

So, 105 kJ of energy (~ 24%) is wasted in boiling 1 L of water. Some of this is used in heating the kettle which is needed to heat the water; but as we only want the hot water arguably it is waste. Obviously this technique can be applied to any heating situation.

Heat of combustion

What if we boiled the kettle on a gas stove? The approach is the same, but it is made more difficult as we need to estimate how much gas was burned. Having done that we just work out, or more likely look up, the heat of combustion of the fuel – in this case natural gas.

Heat of combustion of natural gas (methane) = 50 MJ/kg⁴.

So heat in = 50 MJ for each kg of natural gas burned. The rest of the calculation is as above.

³ ΔT means temperature difference, i.e. hotter temperature minus cooler temperature.

⁴ The European tradition of using Lower Heating Value (LHV) has been used here.

