

Briefing:
Conversion Necessities in Climate and Energy
System Modelling

(alphabetical order)

Lukas Emele, Hannah Förster, Martin Glauer, Christian Hofmann,
Ludwig Hülk, Klara Reder, Mirjam Stappel, Christian Winger

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Contents

1 Introduction	1
2 Definitions	2
3 Unit conversion	3
4 Conversion of greenhouse gas emissions	9
5 Conversion of monetary values	12
6 Conversion of geographic coordinates	16

1 Introduction

With this briefing we provide definitions for units and metrics commonly used in climate and energy modelling.

We provide this briefing, because in climate and energy system modelling, the same data can be represented using a diverse set of units and metrics. This leads to challenges when it comes to comparability and re-use.

Only when we are certain that a variable is measured in a specific unit or metric, we can use it without the chance of producing errors. For example we may want to compare results of different projections with each other or apply a specific variable in our own modelling work.

Sometimes, a conversion is needed which may not be straight forward. With this paper, we aim to make it more straight forward. We take two common situations from climate and energy modelling as the focus for this briefing:

- A researcher is interested in comparing data of key variables from two projections with each other. The two projections have the same key variables but measure them using different units and metrics.
- A researcher is interested in using published data from another model in her own modelling tools. The researcher’s modelling tools require other units and metrics for the data in question.

We identify and describe common units and metrics that are crucial for making data comparable. We cover units in Section 3, greenhouse gases in Section 4, monetary values in Section 5 and geographic coordinates in Section 6

Throughout these sections, we provide – where available – links to conversion tables hosted on the Open Energy Platform¹ (OEP). Like this, we combine what we learn below with practical tools for everyday work.

This briefing may develop further and is open to suggested additions by anyone. Please post suggestions here:

<https://github.com/OpenEnergyPlatform/tutorial/projects/1>. Please attach the label *conversion-briefing*² to your issue.

2 Definitions

In this briefing we distinguish between two things: units and metrics. Both may require conversions at some point. Let us look at two examples at the beginning, before proceeding to our definitions for this briefing:

In energy system modelling, we may be faced with the output variable *final energy consumption*. In one model it may be measured in gigajoule (GJ), in another in kilotons of oil equivalent (ktoe). If we convert both final energy consumption data to a common unit, we can compare both outputs. In this case we converted from one unit to another.

In one model the assumptions on *energy prices* may be valued at Euros as they stood in 2013, in another at Euros as they stood in 2016. Between both years, inflation took place and the values are not directly comparable. We may therefore want to convert (translate) between the two. In this case we converted from one metric to another. We may already suspect that the former process is more straight-forward than the latter. We make this apparent by adopting the following definitions:

Unit of measurement (unit): *A unit of measurement is a standardised quantity of a physical property, used as a factor to express occurring quantities of that property*³. In other words: A unit of measurement is a standardised quantity of a physical quality.

Therefore, conversion from one unit to another is a one-to-one correspondence, i.e. there is one – and only one – correct way to doing it.

¹<https://www.openenergy-platform.org>

²<https://github.com/OpenEnergyPlatform/tutorial/labels/conversion-briefing>

³https://en.wikipedia.org/w/index.php?title=Unit_of_measurement&oldid=9393503

Metric: *A metric is a way to measure something expressed in a specific way.*

In other words; we put something into context. A metric includes a unit and a method. For example measuring different greenhouse gases in the same unit, like kilotons (kt), does not allow for direct comparison of their impact on global warming: Methane (CH₄) emissions are not directly comparable to carbon dioxide (CO₂) emissions as the two gases have different effects on the climate. Only when applying the method of global warming potentials (GWP), both variables can be made comparable. However, different methods may be available. Therefore, converting from one metric to another is not a one-to-one correspondence and the context is an important factor that needs to be documented clearly.

3 Unit conversion

On the OEP:

The OEP provides a table with energy unit names and a lookup-table holding conversion factors. This lookup-table holds conversion factors between the imperial and metric system. It covers energy, mass, length, area and volume units. Both tables are licensed under the Open Data Commons Open Database License 1.0.

- Energy units: https://openenergy-platform.org/dataedit/view/reference/szenariendb_units
- Conversion factors: https://openenergy-platform.org/dataedit/view/reference/szenariendb_conversion

3.1 Mathematical-physical background of unit conversions

A quantity x is represented by the product of a value $\{x\}$ and a unit $[x]$:

$$x = \{x\} \cdot [x] \tag{1}$$

Both the value and the unit can be treated as any other multiplicative factors in formulas.

Example 3.1. A distance $d = 1.23\text{ m}$ has the value $\{d\} = 1.23$ and the unit $[x] = \text{m}$.

In general there is more than one option to express a quantity, namely in different units:

$$x = \{x_1\} \cdot [x_1] = \{x_2\} \cdot [x_2] \tag{2}$$

While the values and units are different, the products of values and units in formula 2 represent the identical quantity x . Also different unit prefixes (milli, kilo, giga, ...) lead to different values.

Example 3.2. The distance $d = 1.23\text{ m}$ from the previous example can also be expressed as $d = 123\text{ cm}$.

Example 3.3. An energy quantity W can be expressed in different units (e.g. *gigajoule* and *megawatt-hour*) and accordingly different values: $W = 7.2\text{ GJ} = 2.0\text{ MW h}$.

A unit conversion is the process of converting between different units and in consequence between different values for the *same* quantity. Conversions between *different* quantities – like conversions from greenhouse gas emissions to emissions of greenhouse gas equivalents (Section 4), or conversion of monetary values (Section 5) – are no unit conversions.

By dividing formula 2 by itself, we can define a conversion factor $C_{[x_1] \mapsto [x_2]}$ between two different units $[x_1]$ and $[x_2]$ of the same quantity x :

$$C_{[x_1] \mapsto [x_2]} = \frac{x}{x} = \frac{\{x_2\} \cdot [x_2]}{\{x_1\} \cdot [x_1]} = 1 \quad (3)$$

The target unit $[x_2]$ is in the numerator while the original unit $[x_1]$ is in the denominator. As $C_{[x_1] \mapsto [x_2]} = 1$ and 1 is the invariant of the multiplication the conversion factor can be multiplied to any term without changing the quantity.

Example 3.4. With a conversion factor $C_{\text{m} \mapsto \text{cm}} = \frac{100\text{ cm}}{1\text{ m}} = 1$ we can convert the distance $d = 1.23\text{ m}$ in centimetre:

$$d = 1.23\text{ m} \cdot C_{\text{m} \mapsto \text{cm}} = 1.23\text{ m} \cdot \frac{100\text{ cm}}{1\text{ m}} = 123\text{ cm}$$

Example 3.5. With a conversion factor $C_{\text{GJ} \mapsto \text{MW h}} = \frac{1\text{ MW h}}{3.6\text{ GJ}} = 1$ we can convert the energy $W = 7.2\text{ GJ}$ in megawatt-hour:

$$d = 7.2\text{ GJ} \cdot C_{\text{GJ} \mapsto \text{MW h}} = 7.2\text{ GJ} \cdot \frac{1\text{ MW h}}{3.6\text{ GJ}} = 2.0\text{ MW h}$$

3.2 SI units, metric units and imperial units

The *International System of Units* (SI⁴) [1] defines seven base units for seven base quantities (see Table 1). Each base unit is connected to a natural constant.

Other units can be expressed through a combination of these basic units. They are derived from the SI. Thus, they are called *SI derived units*. SI base units and SI derived units are collectively often called *metric units*. Those combinations to derive other units from the base units involve exponentiation

⁴Abbreviated from French *Système international d'unités*

Base quantity	Base unit name	Base unit symbol
time	second	s
length	metre	m
mass	kilogram	kg
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	candela

Table 1: SI base units (adapted from [1])

and/or multiplication. The metric area unit is the *square metre* which literally means the square of a metre (m^2) and likewise the volume unit is the *cubic metre* (m^3). More complex units involve both the exponentiation and multiplication. Those units often have a special unit name and symbol.

Example 3.6. We can express *Coulomb*, the unit of the electric charge, as $1 \text{ C} = 1 \text{ A s}$.

Example 3.7. We can express the power unit *Watt* as $1 \text{ W} = 1 \text{ kg m}^2 \text{ s}^{-3}$.

Units like *hour* (h), *litre* (l) and (*metric*) *tonne* (t) are strictly spoken not SI units but are accepted for the use with the SI.

Imperial units were historically defined on a different set of base units, but today they are linked to the SI units. Hence, data expressed in imperial units can be converted to SI units. The conversion table on the Open Energy Platform⁵ holds the appropriate conversion factors. Examples of imperial energy units are British Thermal Unit (Btu) and Therm (thm). Further examples are the length units inch (in), foot (ft) and mile (mi) and the mass unit pound (lb). Like metric units, imperial units can be combined to form other units, for example the pressure unit in the imperial system is *pounds per square inch* (psi) while the pressure unit in the metric system is the *Pascal* ($1 \text{ Pa} = 1 \text{ kg m}^{-1} \text{ s}^{-2}$).

Today most imperial units are *defined* based on SI units. To avoid rounding errors it is good practice to make use of these basic definitions and to not use conversion factors with only one or two decimals. To link this paper to practical applications, the OEP provides conversion factors between the imperial and metric system for energy, mass, and length, area and volume units.⁶

Example 3.8. Given a length of *exactly* $\ell = 1 \text{ ft}$. In the imperial system, 1 in is defined as *exactly* 25.4 mm, so the conversion factor is $C_{\text{in} \rightarrow \text{mm}} =$

⁵https://openenergy-platform.org/dataedit/view/reference/szenariendb_conversion

⁶https://openenergy-platform.org/dataedit/view/reference/szenariendb_conversion

$\frac{25.4 \text{ mm}}{1 \text{ in}}$. As 1 ft is *exactly* 12 in ($C_{\text{ft} \rightarrow \text{in}} = \frac{12 \text{ in}}{1.000 \text{ ft}}$), we can conclude that

$$\ell = 1 \text{ ft} \cdot \frac{12 \text{ in}}{1 \text{ ft}} \cdot \frac{25.4 \text{ mm}}{1 \text{ in}} = 304.8 \text{ mm}.$$

3.3 Conversions of temperatures

Various temperature scales are of the same dimension but their units have different zero points. The *thermodynamic* or *absolute temperature* T has its zero point at absolute zero, the theoretically lowest possible (and practicably never achievable) temperature. The SI unit of the thermodynamic temperature is *Kelvin* (K).⁷

In day-to-day life, temperatures are usually given in relative temperatures with the symbols t or ϑ and the metric unit *degree Celsius* ($^{\circ}\text{C}$) or the imperial unit *degree Fahrenheit* ($^{\circ}\text{F}$). The difference between absolute and relative temperatures can be expressed as

$$\vartheta = T - T_0 \quad (4)$$

where T_0 is the reference temperature of the respective relative temperature scale. For degree Celsius the reference temperature is $T_0(^{\circ}\text{C}) = 273.15 \text{ K}$. This is equal to expressing that absolute zero has the relative temperature $\vartheta_0 = -273.15^{\circ}\text{C}$. For degree Fahrenheit the reference temperature is $T_0(^{\circ}\text{F}) = 255.372 \text{ K}$. Using Fahrenheit, absolute zero has the relative temperature of $\vartheta_0 = -459.67^{\circ}\text{F}$

Additionally, we need to reflect that a temperature interval (temperature difference) of 5°C equals 9°F . From that we can deduce (following formula 4) the conversion factors between degree Celsius and degree Fahrenheit:

$$C_{[^{\circ}\text{C}] \rightarrow [^{\circ}\text{F}]} = \frac{9^{\circ}\text{F}}{5^{\circ}\text{C}} \quad (5)$$

$$C_{[^{\circ}\text{F}] \rightarrow [^{\circ}\text{C}]} = \frac{5^{\circ}\text{C}}{9^{\circ}\text{F}} \quad (6)$$

By applying the previous formulas and dividing by their units we can deduce the conversion formulas from Kelvin to degree Celsius and degree Fahrenheit:

$$\frac{\vartheta}{^{\circ}\text{C}} = \frac{T}{\text{K}} - 273.15 \quad (7)$$

$$\frac{\vartheta}{^{\circ}\text{F}} = \frac{9}{5} \cdot \frac{T}{\text{K}} - 459.67 \quad (8)$$

Example 3.9. How much is 300 K in degree Fahrenheit?

$$\begin{aligned} \frac{\vartheta}{^{\circ}\text{F}} &= \frac{9}{5} \cdot \frac{T}{\text{K}} - 459.67 = \frac{9}{5} \cdot \frac{300 \text{ K}}{\text{K}} - 459.67 \\ \vartheta &= 80^{\circ}\text{F} \end{aligned}$$

⁷There exists also an unit for the absolute temperature in the imperial system: *degree Rankine* ($^{\circ}\text{R}$ or $^{\circ}\text{Ra}$).

A absolute temperature of 300 K corresponds to an relative temperature of 80 °F.⁸

The reciprocal formulas for converting from Celsius or Fahrenheit to Kelvin are:

$$\frac{T}{\text{K}} = \frac{\vartheta}{\text{°C}} + 273.15 \quad (9)$$

$$\frac{T}{\text{K}} = \frac{5}{9} \cdot \left(\frac{\vartheta}{\text{°F}} + 459.67 \right) \quad (10)$$

Example 3.10. How much is 20 °C in Kelvin?

$$\begin{aligned} \frac{T}{\text{K}} = \frac{\vartheta}{\text{°C}} + 273.15 &= \frac{20 \text{°C}}{\text{°C}} + 273 = 293 \\ T &= 293 \text{ K} \end{aligned}$$

A relative temperature of 20 °C corresponds to an absolute temperature of 293 K.

3.4 Specifics in the conversion of energy units

The SI derived energy unit is *joule* which is defined as $1 \text{ J} = 1 \text{ kg m}^2 \text{ s}^{-2}$. It is equal to *watt-second* ($1 \text{ J} = 1 \text{ W s}$). Beyond that, various other energy units exist and a lot of them are used in energy modelling.

Example 3.11. An example of an often used non-SI unit in energy modelling is the *kilowatt-hour* (kW h) which is the product of *kilowatt* (kW) and *hour* (h). As hour is not an SI derived unit⁹ kilowatt-hour is not a SI derived unit either. But as hours can be converted to seconds ($C = 3600 \text{ s h}^{-1}$) also kilowatt-hour can be converted:

$$1 \text{ kW h} = 1000 \text{ W} \cdot 1 \text{ h} \cdot 3600 \text{ s h}^{-1} = 3.6 \cdot 10^6 \text{ W s} = 3.6 \text{ MJ}$$

In energy statistics and energy balances, consumption quantities of fossil fuels are often provided as mass (m) or volume (V). A certain mass or volume of fossil fuels carries a certain amount of energy. Thus, energy (W) can be calculated from mass and volume using mass-specific (H_m) and volumetric (H_V) calorific values:

$$W = H_m \cdot m \quad (11)$$

$$W = H_V \cdot V \quad (12)$$

The calorific values is the amount of heat released by a specific amount of fuel in combustion process. There are two metrics:

⁸To avoid false precision, the result of this calculation should not have more decimals than the input values.

⁹The hour is not a SI derived unit but it is accepted to use with the SI [1].

- *net calorific value* (NCV, H_i) and
- *gross calorific value* (GCV, H_s).¹⁰

The difference between net and gross calorific values is that for the net calorific value it is assumed that water released during the combustion process is in the form of vapour. For the gross calorific value it is assumed that all combustion outputs including water have the same temperature as the fuel input before the combustion process. That means in most practical cases, that vapour condensates to liquid water and hence latent heat from condensation can be used.

The correct choice of net or gross calorific value depends on the context. In Europe, the net heating value calorific value is most commonly used in energy statistics and energy system analysis. The reason is that technical appliances like boilers and motors historically did not use the latent heat in the exhaust gas.

Example 3.12. Gasoline has a volumetric NCV of $H_{i,V} \approx 31 \text{ MJ l}^{-1}$. A typical fuel tank in a car can store $V = 50 \text{ l}$ of gasoline. The energy content W stored in such a fuel tank can be calculated as:

$$W = H_{i,V} \cdot V = 31 \text{ MJ l}^{-1} \cdot 50 \text{ l} = 1.6 \cdot 10^3 \text{ MJ} = 1.6 \text{ GJ}$$

Gasoline has also mass-specific NCV, $H_{i,m} \approx 41 \text{ MJ kg}^{-1}$. A mass of $m = 50 \text{ kg}$ of gasoline has the energy content of:

$$W = H_{i,m} \cdot m = 41 \text{ MJ kg}^{-1} \cdot 50 \text{ kg} = 2.1 \cdot 10^3 \text{ MJ} = 2.1 \text{ GJ}$$

Because of the close relationship between mass and energy quantities and energy quantities for fossil fuels, various energy units were established that look like mass or volume units, but are – in fact – energy units. These units usually carry the term “equivalent” in their names:

- A tonne of (crude) oil carries about 10 Gcal (Gigacalorie) energy. Hence, a *tonne of oil equivalent* (toe) was defined as: $1 \text{ toe} = 10 \text{ Gcal} = 41.868 \text{ GJ}$. This can be interpreted as using in the definition of the tonne of oil equivalent a type of oil with a calorific value of exactly $H_m = 10 \text{ Gcal t}^{-1}$.
- A tonne of hard coal carries about 7 Gcal energy. Hence, a *tonne of coal equivalent* (tce) was defined as: $1 \text{ tce} = 7 \text{ Gcal} = 29.3076 \text{ GJ}$. Again, this can be interpreted as using in the definition of the tonne of coal equivalent a type of coal with a calorific value of exactly $H_m = 7 \text{ Gcal t}^{-1}$.
- A barrel has a volume of approximately 159 l and a barrel of oil carries about 5.8 Mbtu. Hence, a *barrel of oil equivalent* was defined as $1 \text{ boe} = 5.8 \text{ Mbtu} \approx 6.12 \text{ GJ}$.

¹⁰Synonyms are *lower calorific value* (LCV) and *higher calorific value* (HCV) resp. *lower heating value* (LHV) and *higher heating value* (HHV).

Example 3.13. The German energy balance for the year 2018¹¹ provides the primary energy consumption of crude oil as a mass of 87 795 kt and the primary energy consumption of colliery gas (gas from underground mines) as a volume of $451 \cdot 10^6 \text{ m}^3$. It also provides these primary energy consumptions in energy units as 3 731 743 TJ respectively 127 328 tce for crude oil and 8005 TJ respectively 273 tce for colliery gas.

3.5 Tools for unit conversions

Several open-source or free tools are available to assist you with unit conversion:

- *GNU Units*¹² is a shell program that assists not only for simple unit conversions but can perform complex calculations and provide the results in different units.
- *Pint*^{13,14} is a Python package for unit conversions. Own units can be added.
- *WolframAlpha*¹⁵ is a free online computational knowledge engine that is (among other things) capable of unit conversion.

4 Conversion of greenhouse gas emissions

On the OEP:

The OEP provides a lookup-table which holds Global Warming Potential (GWP) values from IPCC Assessment Reports 1–5 for every gas. It also includes information under which legislation (UNFCCC, Montreal Protocol, EU F-Gas Regulation) each gas is governed. The table is licensed under the Datenlizenz Deutschland – Namensnennung.

- GWP values from the IPCC Assessment Reports: https://openenergy-platform.org/dataedit/view/climate/szenariendb_gwp

4.1 Global warming potentials and CO₂ equivalent emissions

Different greenhouse gases have different effects on the climate as they have different radiation properties and differ in how long they remain in the atmosphere (atmospheric lifetime). To make the emissions of different greenhouse

¹¹https://ag-energiebilanzen.de/index.php?article_id=29&fileName=bilanzi18d.xls

¹²<https://www.gnu.org/software/units/>

¹³<https://pypi.org/project/Pint/>

¹⁴<https://pint.readthedocs.io/>

¹⁵<https://www.wolframalpha.com>

gases comparable, several concepts (so called *metrics*) have been developed. The widely accepted and used metric is to calculate *CO₂ equivalent emissions* using *global warming potentials* (GWP).¹⁶

The Intergovernmental Panel on Climate Change (IPCC) provides a definition of the GWP:

The Global Warming Potential (GWP) is defined as the time-integrated RF [radiative forcing] due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO₂ [...].
[2, p. 710]

This means that the GWP is a measure how much additional energy is added to the atmosphere by a specific amount of a greenhouse gas over a time period compared to the effect of the same amount of CO₂. Despite its name, the GWP does *not* measure directly the temperature change (warming) effect.¹⁷

As the GWP depends on the time horizon for which the effect is calculated, this time horizon should always be mentioned. GWP values are typically calculated for 20 years, 100 years and 500 years and often written as GWP₂₀, GWP₁₀₀ and GWP₅₀₀.

In most cases the GWP₁₀₀ is used as the GWP₁₀₀ is mandatory for reporting. For example, the GWP₁₀₀ was *adopted as a metric to implement the multi-gas approach embedded in the UNFCCC and made operational in the Kyoto Protocol* [3]. These GWPs are used in reporting of greenhouse gas data to the United Framework Convention on Climate Change (UNFCCC)¹⁸, the Kyoto Protocol and the European Union. Not only are the GWP₁₀₀ used for official reporting requirements, they have also become a standard metric for almost any modelling that includes reporting on greenhouse gas emissions. The period of 100 years was chosen as the atmospheric lifetime of CO₂ was initially estimated as 100 years. Additionally it is a compromise between the effects of long-lived and short-lived gases.

GWPs are not measured but calculated. As the knowledge of climate science progresses, the GWP values are updated with every IPCC Assessment Report.

Other metrics exist (e.g. GTP¹⁹, GWP*²⁰). But as the GWP₁₀₀ is mandatory for international reporting and has become the standard metric, other metrics are rarely used in energy system modelling. Hence, we do not describe other metrics than GWP in this briefing.

¹⁶A detailed explanation of CO₂ equivalent emissions and global warming potentials is given in the latest IPCC Assessment Report [2, chapter 8.7 and specifically section 8.7.1.2].

¹⁷In fact, the IPCC states: *Thus, the name 'Global Warming Potential' may be somewhat misleading, and 'relative cumulative forcing index' would be more appropriate.* [2, p. 711]

¹⁸<https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/frequently-asked-questions/global-warming-potentials-ipcc-fourth-assessment-report>

¹⁹Global temperature change potential

²⁰Alternatively defined global warming potential, discussed e.g. by [4]

4.2 Calculation of CO₂ equivalent emissions

CO₂ equivalent emissions E_{eq} can be calculated using the emissions of individual gases E_{GHG} and the global warming potentials of these gases:

$$E_{\text{eq}} = \sum^{\text{GHG}} E_{\text{GHG}} \cdot GWP_{\text{GHG}} \quad (13)$$

On the OEP you can find a table with all GWPs from the IPCC Assessment Reports 1 to 5: https://openenergy-platform.org/dataedit/view/climate/szenariendb_gwp

Example 4.1. The combined climate effect over a 100 year horizon of the emissions of 100 Mt CO₂, 0.5 Mt CH₄ (methane) and 0.2 Mt N₂O (nitrous oxide) can be calculated using the GWP values from the latest IPCC Assessment Report [2]:

$$\begin{aligned} E_{\text{eq}} &= E_{\text{CO}_2} \cdot GWP_{\text{CO}_2} + E_{\text{CH}_4} \cdot GWP_{\text{CH}_4} + E_{\text{N}_2\text{O}} \cdot GWP_{\text{N}_2\text{O}} \\ &= 100 \text{ Mt} \cdot 1 + 0.5 \text{ Mt} \cdot 28 + 0.2 \text{ Mt} \cdot 265 \\ &= 167 \text{ Mt} \end{aligned}$$

So the combined effect of the CO₂, CH₄ and N₂O emissions is equivalent to the emission of 167 Mt CO₂. A common and often used – but fuzzy – statement is: “167 Mt CO₂ equivalents were emitted.”

A special case are CO₂ emissions from biomass combustion. During their lifetime plants extract CO₂ from the atmosphere to grow. During the combustion of biomass the same amount of CO₂ is emitted that were extracted by the plants before. Thus the CO₂ emissions from biomass combustion are usually excluded from CO₂ equivalents.²¹ This can be done in two ways:

- Emissions are calculated with CO₂ emission factors of zero for biofuels.
- CO₂ emissions from biofuels $E_{\text{eq}}^{\text{bio}}$ are subtracted from CO₂ equivalent emissions:

$$E'_{\text{eq}} = \left(\sum^{\text{GHG}} E_{\text{GHG}} \cdot GWP_{\text{GHG}} \right) - E_{\text{eq}}^{\text{bio}} \cdot GWP_{\text{CO}_2} \quad (14)$$

²¹The IPCC provides a more detailed explanation on the exclusion rules, see question Q2.10 in the IPCC's FAQ: <https://www.ipcc-nggip.iges.or.jp/faq/faq.html>

Example 4.2. If we assume that in the previous example of the 100 Mt CO₂ are actually 15 Mt CO₂ from burning of biofuels, then the calculation changes to:

$$\begin{aligned}
 E'_{\text{eq}} &= E_{\text{CO}_2} \cdot GWP_{\text{CO}_2} + E_{\text{CH}_4} \cdot GWP_{\text{CH}_4} + E_{\text{N}_2\text{O}} \cdot GWP_{\text{N}_2\text{O}} \\
 &\quad - E_{\text{CO}_2}^{\text{bio}} \cdot GWP_{\text{CO}_2} \\
 &= \left(E_{\text{CO}_2} - E_{\text{CO}_2}^{\text{bio}} \right) \cdot GWP_{\text{CO}_2} + E_{\text{CH}_4} \cdot GWP_{\text{CH}_4} + E_{\text{N}_2\text{O}} \cdot GWP_{\text{N}_2\text{O}} \\
 &= (100 \text{ Mt} - 15 \text{ Mt}) \cdot 1 + 0.5 \text{ Mt} \cdot 28 + 0.2 \text{ Mt} \cdot 265 \\
 &= 152 \text{ Mt}
 \end{aligned}$$

Thus, the CO₂ equivalent emissions are lower, since we excluded the CO₂ emissions from burning biofuels.

Please note: During the combustion of fuels not only CO₂ but also CH₄ and N₂O are emitted. A common mistake is to exclude *all* emissions from biofuel combustion from CO₂ equivalent emissions and not only the CO₂.

5 Conversion of monetary values

If we want to compare monetary values with one another, conversion metrics become necessary. Use cases of monetary conversions within climate and energy system modelling can be found in the inflation adjustment of monetary values or in the comparison of prices or GDP values referring to different base-years.

Nominal values and real values: As we know, the prices of goods, services, wages, etc. change over time t . Two types of monetary values exist that express different aspects: nominal values and real values. The nominal value measures the value of a good, market basket or a nations economic performance in terms of money, which e.g. depends on the inflation rate. The real value measures against goods or services. It is adjusted for inflation and excludes its effect. Thus, it enables us to express the value of a good in a comparable manner related to the value of this good in a given base-year.

Example 5.1. An apple may have cost 1.00 € in 2010 and 1.00 € in 2015. Between 2010 and 2015 inflation took place, so in 2015 one could buy less for 1.00 € than in 2010. If the apple still cost 1.00 € in 2015 including inflation, this means that the apple in 2015 was in fact cheaper than in 2010.

Since prices change over time t , it is important to define, which points in time we are looking at. The inflation adjustment of a value always needs the reference to a certain base-year t_0 . P_0 is the price of a good of market basket in the base-year t_0 . And P_t is the price of a commodity bundle or good at a time t .

Price indices and GDP: A price index p_t represents the change of the price of a good or commodity bundle between a base-year t_0 and any other point in time t . The price index p_0 for the base-year t_0 is usually set to 100. [5]

An example for such a price index are consumer price indices, which are statistically estimated using the prices of a sample of representative items whose prices are collected periodically.²² [5]

At every point in time, a certain price index refers to the same good or commodity bundle which is a fixed list of items in given proportions. If we are not just looking a certain good or commodity bundle, but at the economy of a whole country, its performance can be measured by the *gross domestic product* GDP²³. GDP is a monetary measure of the market value of all the final goods and services produced in a specific time period in a national economy. A price index is too static a measure here, thus we use an index called (*implicit*) *GDP deflator*, which takes into account that the items inside the “national market basket” may change over time. The implicit GDP deflator can be viewed as a measure of general inflation in the domestic economy²⁴.

Statistical offices such as eurostat calculate implicit GDP deflators by dividing the aggregate (GDP) measured in current prices by the same aggregate measured in constant prices. For GDP for example, eurostat calculates it from seasonally and calendar adjusted GDP values rescaled so that 2010 = 100.²⁵ The OECD does so for 2015 = 100.²⁶

5.1 Inflation

For our explanation, we take a look at a certain year A . For this year, we know the nominal value (actual price) Q_A of a good X and the change in its price p_A (price index / deflator) since base-year t_0 . p_0 is set to 100, as described above. The real value R_A of a good X can be calculated as follows in equation 15:

$$R_A = Q_A \cdot \frac{p_0}{p_A} \quad (15)$$

Now we can compare the real values of year A with the base-year. For the comparison with the base-year, we can calculate the inflation. It measures the increase in the price level p_t of goods and services over a period of time, i.e. between the time $t = A$ and $t = B$. It is shown in equation 16

²²https://en.wikipedia.org/wiki/Consumer_price_index

²³https://en.wikipedia.org/wiki/Gross_domestic_product

²⁴<https://www.gov.uk/government/publications/gross-domestic-product-gdp-deflators-user-guide/gdp-deflators-user-guide>

²⁵<https://data.europa.eu/euodp/en/data/dataset/K3pdexT1mI0wri6SuatQ>

²⁶<https://stats.oecd.org/Index.aspx?DataSetCode=MEI>

$$i_{BA} = \frac{p_B - p_A}{p_A} \cdot 100 = \left(\frac{R_B}{R_A} - 1 \right) \cdot 100 \quad (16)$$

As an example, we can take a look at “real” data²⁷ from the statistical office of the European Union Eurostat. The dataset contains the GDP of the European Union in total and for each of its Member States. A detail of the data set is shown in table 2.

GDP of Bulgaria	unit	2010	2011
Current prices (<i>real values</i>)	<i>Mio</i> €	38,044.1	41,252.6
Chain linked volumes (<i>nominal values</i>)	<i>Mio</i> €	38,044.1	38,938.5
Chain linked volumes index	–	100	102.4

Table 2: Bulgaria’s change in GDP between 2010 and 2011. Source: Eurostat: *GDP and main components (output, expenditure and income)*, assessed in July 2020.²⁹

Example 5.2. Let’s compare Bulgarias GDP from $t_1 = 2011$ with base-year $t_0 = 2010$. The nominal values for the $GDP_{nom,2011}$ is 41,252.6 million €. The real value $GDP_{real,2011}$ is also given with 38,938.5 million €. It is calculated by Eurostat using a GDP deflator.

As the chain linked volume indices show, the GDP grew from 100 to 102.4 by 2.4%. This can also calculated manually by means of equation 16.

5.2 Deflation

This use case involves deflation to make two values expressed in monetary terms comparable to one another. Let’s assume this is GDP. To compare a nominally expressed GDP with a GDP expressed in real terms we need to convert the nominal GDP into real GDP with the same base-year as the GDP expressed in real terms. To do so, we make use of the implicit GDP deflator D :

$$GDP_{real} = \frac{100}{D} \cdot GDP_{nominal} \quad (17)$$

Example 5.3. Converting nominal values to real values

Country X’s GDP for 2018 is expressed in nominal Euro and its value is assumed 110 € in study 1 (GDP A). Country X’s GDP for 2018 is expressed in real values of the year 2015 and its value is assumed 110 € in study 2 (GDP B). We want to compare both values with one another. We will thus need to find the GDP deflator with which we can convert GDP A from its

²⁷https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_gdp&lang=en

nominal value to its value expressed at base-year 2015 as GDP B. We know that deflators provided by OECD are set to 2015 = 100. The deflator given to convert from nominal values 2018 to real values 2015 is 103.79^a and expresses that 100 € in 2018 would equal 103.79 € in 2015. Thus, to make both GDP values comparable, we proceed as follows by making use of equation 17:

$$(100 / 103.79) \text{ GDP A} = 96.34.$$

This tells us that the GDP assumed in study A is actually less than the GDP assumed in study B. The table below summarises the data used in this example.

Variable	Year	Metric	value
GDP A	2018	€	110
GDP B	2018	€ (2015)	110
Deflator	2018	2015 = 100	103.79
GDP A	2018	€ (2015)	96.34

^ahttps://stats.oecd.org/BrandedView.aspx?oeid_bv_id=mei-data-en&doi=data-00052-en#

Example 5.4. Converting two nominal values into real values with the same base-year

Country X's GDP for 2018 (GDP18) is expressed in nominal terms and its value is 110 million €. Country X's GDP for 2014 (GDP14) is expressed in nominal terms and its value is 110 million €. We want to compare both values with one another to learn whether GDP between 2014 and 2018 changed in real terms. To do so, we will need to find the GDP deflators with which we can convert both values to a common base-year. We know that deflators provided by OECD are set to 2015 = 100. The deflator given to convert from nominal values 2018 to real values 2015 is 103.79 and from 2014 to 2015 it is 98.30.^a and expresses that 100 € in 2018 would equal 103.79 € in 2015 and that 100 € in 2014 would equal 98.30 € in 2015. Thus, to make both GDP values comparable and expressed in real terms of the year 2015, we proceed as follows by making use of equation 17:

$$(100 / 103.79) \text{ GDP18} = 96.34.$$

$$(100 / 98.30) \text{ GDP14} = 111.90.$$

Thus, real GDP of country x declined from 111.90 in 2014 to 96.34 in 2018. The table below summarises the data used in this example.

Variable	Year	Metric	value
GDP	2014	€	110
GDP	2018	€	110
Deflator	2014	2015 = 100	98.30
Deflator	2018	2015 = 100	103.79
GDP	2014	€ (2015)	111.90
GDP	2018	€ (2015)	96.34

^ahttps://stats.oecd.org/BrandedView.aspx?oeid_bv_id=mei-data-en&doi=data-00052-en#

Practical tip:

In everyday use you can identify whether a monetary value is expressed in nominal or real terms by checking whether the currency name or symbol is followed the indication of a year or not. If it is not, it is very likely a nominal value, e.g. expressed as 100 €. If you encounter such or similar notation, these are expressed as real values: 100 €(2015). 100 €('15).

6 Conversion of geographic coordinates

To reference any given location in space, a coordinate reference system (CRS) is needed. As most of the location data we are interested in is somewhere on earth, or very close to it, we need a CRS that is used for locating places on earth. Such a CRS is called a geodetic reference system³⁰. The World Geodetic System, which is used for the Global Positioning System (GPS) has become the de-facto standard CRS and is generally used to specify coordinates. The latest version is called WGS 84³¹. Often, when no reference system is documented, WGS 84 is implied, but not making any reference to a CRS is bad practice. CRS can be referenced using an EPSG code.³²

Every geodetic reference system comes with an ellipsoid, which is a mathematical three dimensional surface, approximately describing the shape of the earth. While there are many CRS, the number of ellipsoids is relatively small and conversions between CRS using the same ellipsoid is relatively unproblematic.

There are free software tools available that can create conversions automatically^{33,34,35}. When converting between different ellipsoids, errors will occur. This is easy to imagine when using an analogy. When you are putting pins in a grid on one potato, it is impossible to replicate that same grid on a different potato. At some point in three dimensional potato space, the distance between two pins will have to diverge and there is no way of accounting for this. So conversions between ellipsoids are always approximations and should be avoided if not strictly necessary.

Conversion of points between different CRS using the same ellipsoid are possible without any errors. However there is a difficulty when dealing with lines. A line is generally stored as a connection between two points. When looking at a line, it may be straight in one CRS, but curved in another. This curving effect is not always taken into account. The effect adds up in polygons

³⁰Synonyms for geodetic reference system include the shorter “geodetic system” and “geodetic datum”

³¹WGS 84 = World Geodetic System 1984

³²see: https://www.w3.org/2015/spatial/wiki/Coordinate_Reference_Systems

³³proj: <https://proj.org/about.html>

³⁴proj4: <http://proj4js.org/>

³⁵QGIS: https://docs.qgis.org/3.10/en/docs/user_manual/working_with_projections/working_with_projections.html

and bodies. With all these potential conversion errors in mind, we should also state that when using the commonly available conversion tools, the resulting derivations are often negligibly small. A description on how to convert between different CRS in a PostgreSQL database is given in 6.1.

As the distinction between ellipsoids, CRS and map projections are sometimes blurry, here is a short description of a map projection: A map projection is a mathematical function used to flatten the three-dimensional shape of the earth to a two-dimensional plane. Map projections always have to be a compromise between equal area, angle and distance representation. Any projection can only get two out of these three right at the same time. Map projections can be universally combined with coordinate systems and ellipsoids, but some are better geared to work with one another.

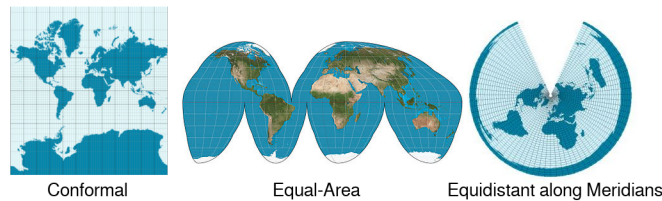


Figure 1: Conformal, Equal-Area and Equidistant Map Projections (Mercator, Goode-Homolosine and Equidistant Conic Projection respectively)³⁷

6.1 Vector Data

Geographic vector information is expressed via points, lines, polygons and combination of these types. Conversion into other systems is always possible, but may produce an error.

- A **point** is stored as a combination of its two coordinates – x and y – in a reference system and its attributes. Converting a point to a different coordinate system is generally straight forward and produces no error, unless the ellipsoid changes.
- A **line** is stored as a connection between a starting point A and an ending point B, or more points, each with coordinates. As described in chapter 6, conversion of lines into a different CRS can produce an error.
- A **polygon** is stored like a line with the starting and ending point being the same. Several polygons can be combined to create polygons with holes. Conversion of polygons may produce the same error as observed in lines.

³⁷Figure CC-BY-SA 3.0 adapted from Mercator-proj <https://commons.wikimedia.org/wiki/File:Mercator-proj.png>, Goode homolosine projection SW https://commons.wikimedia.org/wiki/File:Goode_homolosine_projection_SW.jpg, Kegelprojektion https://commons.wikimedia.org/wiki/File:Kegelprojektion_laengentreu_kl.jpg

Allowing for a third dimension adds a height – or z-coordinate – to objects. This allows for representing bodies. The same potential conversion errors as for lines and polygons apply.

In a PostgreSQL database coordinates of all types of vector objects can easily be converted using the PostGIS extension. The following example uses the outlines of a building in central Europe. The object is stored in a CRS with the EPSG-code 32633³⁸. The Object looks like this:

```
building
POLYGON((319121 5697216, 319364 5697174, 319350 5697096, 319108
5697138, 319121 5697216))
```

To get the same object in a different CRS we are using the PostGIS function `ST_TRANSFORM`. The object's geometry is stored in a column called `geom`. The database can determine the CRS from that column, so we only need to supply the target CRS. In this case we are converting to WGS 84, which has the EPSG code 4326.

```
SELECT ST_TRANSFORM(building.geom, 4326) as building_in_WGS84
```

The converted object `building_in_WGS84` looks like this:

```
building_in_WGS84
POLYGON((12.3998 51.3973, 12.4033 51.3970, 12.4031 51.3963,
12.3996 51.3966, 12.3998 51.3973))
```

6.1.1 Conversion of bounding boxes

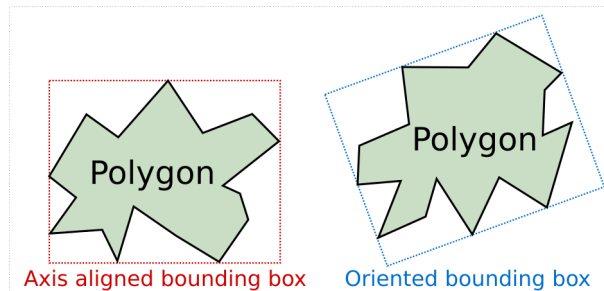


Figure 2: Axis aligned and oriented, 2-dimensional Bounding Boxes

A bounding box is a 2-dimensional vector rectangle or a 3-dimensional vector cuboid, containing the object of interest. Bounding boxes allow for much accelerated calculations, due to the simplified shape in comparison to the original.

In many applications the bounding box is aligned with the axes of the coordinate system, and it is then known as an axis-aligned bounding box (AABB). An arbitrary bounding box is sometimes called an oriented bounding box (OBB),

³⁸32633 is the EPSG-Code for WGS 84, UTM zone 33N

or an OOB when an existing object's local coordinate system is used. AABBs are much simpler to test for intersection than OBBs, but have the disadvantage that when the model is rotated they cannot be simply rotated with it, but need to be recomputed.

Bounding boxes are simply a sub group of vector data and can be converted with the same tools.

6.1.2 Note on axis order in geospatial data

Geodetic systems specify an order in which to give axes. One of the most common coordinate systems (WGS 84) defines the axis order as latitude first, followed by longitude. This can also be observed for instance in Google Maps. Typically geodetic systems follow this order. However not all applications do. Most data formats and database systems prefer an order where longitude comes first and is followed by latitude, as it represents x followed by y order used in mathematics and computer graphics. The GEOJSON format for instance states that “coordinates are assumed to be WGS 84 *with reversed axes*”.³⁹

Since the formats are standardised, this usually doesn't create any problems. When converting geospatial data or loading it into a database however, it's best to check again and make sure that the axis order is in line with the expectation.

6.2 Raster Data

Another way to represent geographic information is to use a raster. A common example for this is aerial photography or satellite imagery. Every raster cell, or pixel, of the photo can be allocated to specific coordinates in a reference system. It is also possible to create a raster with measured values in every cell. Raster data allow for a heterogeneous representation of an area. While transformations of raster data are also possible with the `ST_TRANSFORM` command, it should be used rarely and with care. Every pixel of an image is not a point, but a square, representing the area that it covers. When translating a raster to a different CRS, the transformed pixels do no longer cover the same area. This leads to a misrepresentation of the area or changes in the values of every cell.

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³⁹see: https://www.w3.org/2015/spatial/wiki/Coordinate_Reference_Systems

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