Sustainability Summary

1. Planet Earth

We only have one planet. We should thus be careful with it. In this chapter, we're going to look at how our planet is doing.

1.1 Basic principles of sustainability

What does sustainability actually mean? And how do we accomplish it? We will first exam these basic ideas.

1.1.1 Sustainable Development

Sustainable Development (SD) is a development that meets the needs of the present. However, it also makes sure that future generations can meet their needs. To achieve a Sustainable Development, we should aim to reach an **equilibrium**. The load we put on our environment should be equal to its ability to recover from it.

An important principle for SD is the **precautionary principle**. Let's suppose there is some action or policy that might cause serious harm to the public. The precautionary principle now states that those in favor of the action/policy need to prove that it's safe. In other words, you can better be safe than sorry.

1.1.2 Ideas of sustainability

The Earth may seem like something that has always been present, and will always be present as well. But when you go up into space, your view on matters will change. You will see that not space is unique, but the Earth is. It is our space ship, and we need to take care of it.

At the moment, we're more or less destroying our own Earth. This needs to change. To accomplish this, everyone should want to change. The basic idea behind the change is to work with nature, rather then against.

1.2 Keeping the Earth in balance

The Earth is a unique planet. Its temperature is ideal to support life. It would be nice to keep this temperature level in balance. What factors influence this level?

1.2.1 Energy entering and leaving our planet

The sun emits a lot of light towards planet Earth. This light arrives with an intensity (called the **solar intensity**) of $S_0 = 1372 W/m^2$. Planet Earth has a reflection of approximately $\alpha = 30\%$. (This is called the **albedo**.) It thus absorbs 70% of S_0, which is $960 W/m^2$. We can even say that, in total, our planet absorbs

$$E_{in} = (1\alpha) S_0 A_{sun} = (1 - \alpha) S_0 \pi R^2, \tag{1.2.1}$$

where A_{sun} is the area which is shined on by the sun. Also, $R = 6371 km$ is the Earth radius.

Our planet doesn't only absorb energy. It also emits it. The total outgoing energy is given by **Boltzmann's law**. It states that

$$E_{out} = \sigma T^4 A_{earth} = \sigma T^4 4\pi R^2, \tag{1.2.2}$$

where A_{earth} is the surface area of the Earth, and T is its temperature. Also, $\sigma = 5.670 \cdot 10^{-8} W/m^2K^4$ is **Stefan's constant**. If we equate $E_{in} = E_{out}$, then we would find that the **equilibrium temperature** of the Earth is $T_{eq} = -18°C$. Luckily, this isn't the actual temperature of our planet. This is because of the **greenhouse effect**.

1.2.2 The greenhouse effect

To see how the greenhouse effect works, we need to examine the way our Earth is heated. First, we receive electromagnetic waves (which include visible light) from the sun. These waves occur mainly in the visible spectrum. Since our atmosphere is transparent for these waves, they can reach the planet's surface, thus heating it.

The Earth also emits radiation back into space. However, this radiation mainly occurs in the infra-red part of the spectrum. And our atmosphere can absorb this kind of radiation. Most of the radiation thus doesn't make it into space. It only warms up the atmosphere, which, in turn, warms up the planet surface again.

The greenhouse effect isn't necessarily bad. Without it, we'd have a temperature of $-18°$. However, we can insert too many greenhouse gases into our atmosphere. (**Greenhouse gases**, like **carbon dioxide** (CO_2), cause our atmosphere to absorb even more infra-red radiation.) If we do this, the planet's temperature will increase. And that's not very good, since it may cause our climate to change.

1.2.3 Climate change

The term **climate** refers to the the average state of our environment. If we talk about **climate change**, we mean the variation of this climate over time. We only take into account long-term variations, spanning at least a few decades. A specific example of climate change is **global warming**.

To prevent climate change, the **United Nations Framework Convention on Climate Change** (UNFCCC, or shorter, FCCC) was created. It is an international environmental treaty. Almost all countries on Earth have agreed upon it. (Sadly, the USA tends to be rather stubborn.) Its goal is to achieve the right level of greenhouse gas concentrations in the atmosphere.

There is also the **Intergovernmental Panel on Climate Change** (IPCC). The task of this panel is to examine the risk of climate change, caused by human activity. The IPCC does not carry out research itself. Instead, it publishes reports, based on published scientific literature. The most important conclusion of the IPCC, is that the temperature of the Earth is increasing. This temperature increase then causes all sorts of bad effects.

1.2.4 Natural causes of climate change

Let's ask ourselves, what natural phenomena can cause climate change? The **Milankovitch Theory** describes some of these causes. It states that climate change is caused by changes of Earth's orbit. This happens in multiple ways. First of all, the eccentricity of our orbit changes periodically. The Earth rotation axis (with respect to the orbital plane) also shifts slightly over time. Finally, Earth's orbit is subject to a minor precession (rotation in the orbital plane). All these changes occur periodically. Earth's climate thus also changes cyclically.

Next to the Milankovitch Theory, also other causes of climate change are known. The **continental drift** is known to cause climate changes as well. As the continents shift, the Earth can reflect more/less radiation. This thus shifts the Earth's energy balance.

The Milankovith Theory and the continental drift both cause long-term climate changes. There are also short-term natural climate changes. These are mainly caused by variations in the solar intensity. This, in turn, is often caused by so-called **solar spots**. Finally, big **vulcanic eruptions** and **large scale weather systems** (like El Niño) are also known to cause climate change.

1.2.5 Human causes

Not all climate changes are caused by natural phenomenon. Humanity also influences the climate. We do this in many ways. Sadly, most of these ways aren't understood.

However, one cause of climate change that is understood, is the greenhouse effect. In previous centuries, the concentration of greenhouse gases used to be a steady $280PPM$. (PPM means parts per million.) However, over the past century, this concentration has risen to $390PPM$. This rise has caused the average temperature of the Earth to rise by almost an entire degree Centigrade.

1.3 Monitoring planet Earth

To know how to save the Earth, we first need to know what's wrong. We thus need to observe the Earth. To accomplish this, several projects are currently active. (Is the Ozone hole growing? How is El Nino doing? Are the rain forests and the ice caps still shrinking?) But how do those projects work? How do we acquire data about our environment?

1.3.1 Going back into history

There are many ways in which we can find out something about the history of our environment. Of course, there are scientific records for the past century. But if we want to have data about our world centuries, or even millennia ago, we need different methods. If we are only interested in a few centuries, we can examine **tree rings** and **plant remains**. If, however, we want to go back several millennia, we have to examine **isotopes** and **fossiles**.

1.3.2 Detecting water isotopes

Let's consider an example. We will examine water. Water has one oxygen molecule O and two hydrogen molecules H. It is thus described by H_2O. Usually, H has an atomic weight of $1u$ and O an atomic weight of $16u$. (H_2O thus weighs $18u$.) However, some water molecules (about 0.21%) have an O atom with an atomic weight of $18u$. (This atom has two more neutrons.) We call this variant the ^{18}O-variant. (It is also possible for water molecules to have a ^2H deuterium atom. The working principle for this is the same. We won't consider this specific case though.)

There is a way to find the percentage of ^{18}O-variant molecules. To do this, we use a **mass spectrometer**. The working principle of this is as follows. First, we ionize the molecules, so they become HO^-. (They lose a hydrogen atom.) We then send a beam of these ionized water molecules into an electric field. This field bends the trajectory of these particles. The ^{16}O-variant and the ^{18}O-variant have the same charge. So the same Lorentz forces are acting on them. However, the ^{18}O-variant is more heavy than the ^{16}O-variant. It therefore bends off less. In this way, the percentage of ^{18}O-molecules can be found.

1.3.3 The meaning of the water isotopes

You may wonder, what's the use of examining water isotopes? To find that out, we define

$$\delta^{18}O = \frac{\left[\text{Percentage } ^{18}O\text{-variant in vapor}\right] - \left[\text{Percentage } ^{18}O\text{-variant in water}\right]}{\left[\text{Percentage } ^{18}O\text{-variant in water}\right]}. \tag{1.3.1}$$

Usual values for the above equation are

$$\delta^{18}O = \frac{0.208\% - 0.210\%}{0.210\%} \approx -0.01 = -1\% = -10 \text{ promille}. \tag{1.3.2}$$

In general, we have $\delta^{18}O < 0$. Now let's ask ourselves, why? To find that out, we look at the energy of a molecule. It is given by

$$E = \frac{1}{2}kT = \frac{1}{2}mV^2, \tag{1.3.3}$$

with k a constant, T the temperature, m the mass and V the velocity. The temperature (and thus the energy) of the molecules in a fluid is generally equal. So we must have

$$\frac{1}{2}m_{16}V_{16}^2 = \frac{1}{2}m_{18}V_{18}^2. \tag{1.3.4}$$

The ^{18}O-variant has a higher mass. So it must have less velocity. It thus escapes less easily from water. This means that it evaporates less easily than the ^{16}O-variant. This explains why $\delta^{18}O$ is negative.

Now let's examine the effects of temperature. If the temperature T increases, also the velocities of the molecules increase. At these high velocities, the difference between V_{16} and V_{18} is less important. So the two variants evaporate at a more equal rate. This means that the magnitude of $\delta^{18}O$ is smaller for high temperatures. $\delta^{18}O$ is therefore (relatively) highly negative on the poles.

By using this trick, we can find the temperature of our planet over the past centuries. Every year, layers of snow are forming on the poles. As these layers are compressed to ice, small bubbles of air are trapped in them. Both the snow and the trapped air have a set value of δ^{18}. We can then drill up several layers of ice from the poles. For every layer, we can then find the temperature at the time the layer was formed.

Next to using surface ice, it is also possible to use **ocean sediments**. You then have to start drilling in the ocean floor.

1.3.4 Using carbon contents in plant remains

Let's suppose we find plant remains. How do we know how old they are? To do that, we can use a method called **carbon dating**. In the atmosphere is not only the normal ^{12}C carbon variant, but also ^{14}C. The isotope ^{14}C is radioactive, but it decays only very slowly.

A living plant, being in contact with the atmosphere, has the same $^{14}C/^{12}C$ ratio as its surroundings. However, when a plant dies, it won't replenish its supply of ^{14}C anymore. Over time, the ^{14}C is subject to radioactive decay. The $^{14}C/^{12}C$ ratio will thus decrease. This happens in a negative exponential way. From this ratio, scientists can derive how long ago the plants have died.

2. Non-renewable energy

In this chapter, we're going to look at non-renewable energy sources. Where do they come from? And what are the consequences of using them?

2.1 Fossil fuels

Currently, fossil fuels provide 85% of the world's energy. The most important types of fossil fuels are coal, natural gas and crude oil (petroleum). Where do those fuels come from? And what are their differences?

2.1.1 Fossil fuels

To investigate fossil fuels, we first look at how they're 'made.' Millions of years ago, plant remains were pressed, by the forces of nature, into so-called **geological reservoirs**. Due to the high pressure, these plant remains slowly turned into fossil fuels. This happened over the course of millions of years.

Now these fuels are mined and burned. This burning causes CO_2 to come into the atmosphere. This CO_2 is then used by plants again, to grow. So in a way, there is a cycle. Plants turn to oil, which is burned to CO_2, which is then again absorbed by plants. It may thus seem like using fossile fuels is sustainable. However, it is not. This is because fossile fuels were formed over millions of years. But, we use up all the fossile fuels of our planet in only a few centuries.

2.1.2 Coal

Coal is fossilized, condensed, carbon-rich fuel. It is quite abundantly present on our planet. It provides about 24% of the world's energy. And, at the present rate of consumption, we won't run out of coal for 200 more years.

However, using coal isn't very efficient. When creating energy, 65% of it is lost in powerplants, and 10% more is lost in energy transport. And there is an even worse downside to coal. Coal is very carbon-rich. So when burning it, a lot of CO_2 appears. This causes the greenhouse effect problems to grow significantly.

2.1.3 Natural gas

Natural gas mainly consists of **methane** (CH_4). It has a few downsides to coal. It is generally difficult to transport. And at our current rate of consumption, we will run out of gas in 60 years.

However, natural gas is a lot cleaner than coal. This is mainly because it's more efficient. Only 10% of the energy is lost during the conversion of gas to electricity. Natural gas also contributes less to the greenhouse effect. This is because the gas contains hydrogen atoms. When natural gas is being burned, not only CO_2 is formed, but also H_2O. When this H_2O is formed, energy is produced. However, H_2O doesn't really effect the greenhouse effect.

2.1.4 Crude oil (petroleum)

Crude oil can be described as buried organic matter. It is rich in **hydrocarbons**, being molecules with carbon chains of various lengths. Attached to these carbon chains are hydrogen molecules. The ratio of hydrogen atoms to carbon atoms is about $8:5$. This is lower than the ratio of natural gas $(4:1)$, but higher than the ratio of coal. For this reason, crude oil is less clean than natural gas, but more clean than coal.

Oil is usually **distilled**: It is broken up in fractions, based on the molecule length. Examples of parts are **gasoline** (with chains of 5 to 12 carbon atoms), **diesel** (10 to 15 carbon atoms) and **kerosene** (12 to 15 carbon atoms).

2.2 Handling energy

2.2.1 Energy sources

Our planet uses up a lot of energy. It gets this energy out of so-called **energy sources**. We can distinguish two types of energy sources.

First, there are the **non-renewable energy sources**. These sources include fossile fuels and nuclear energy. Non-renewable sources contain energy. But once that energy has been released, the energy source is lost. For this reason, they are finite.

On the other hand, there are the **renewable energy sources**. Examples are wind, water and solar energy. Renewable energy sources are either regenerative or (virtually) inexhaustible.

2.2.2 Dangers of linear predictions

Previously, we have often used the words ‘based on the current rate of consumption.’ When we use this line, we assume that the rate of consumption remains constant. However, the rate of consumption generally does not remain constant. It usually grows by a (more or less) constant percentage every year. Linear predictions therefore do not work. Instead, the rate of consumption increases exponentially.

Let’s consider a country X. We suppose that the oil consumption of this country increases by a constant percentage of 5% every year. Using this, we can calculate the **doubling time**. This is the time it takes for the consumption (or any other magnitude) to double. You can find the doubling time (approximately), by dividing 70 by the rate of growth. For country X, the oil consumption thus has a doubling time of $70/5 = 14$ years.

The doubling time has an important property. During every doubling time, more oil (or other quantity) is used than in all the previous years. (This follows from the exponential relation.) In other words, country X used more oil in the last 14 years alone, than in all the previous centuries together.

2.2.3 Transforming energy

From↓ To→	**Chemical**	**Electrical**	**Heat**	**Light**	**Mechanical**
Chemical	chemical reactions	battery/fuel cell	fire	fire	engine/rocket
Electrical	battery	transformer	radiator	light bulb	electric engine
Heat	gasification	thermocouple	heat exchanger	fire	steam engine
Light	photosynthesis	solarcells	radiation	prisma	solar sail
Mechanical	heat cell	dynamo/generator	friction	flint spark	gearbox

Table 2.1: Methods to transform on type of energy into another.

It’s nice to have energy sources. But an energy source itself is not really useful yet. This energy needs to be transformed to another kind of energy. Important forms of energy are **chemical energy**, **electrical energy**, **heat**, **light** and **mechanical energy**. Methods to convert from one of these states to another can be seen in table 2.1.

The principle of **conservation of energy** states that energy is conserved. When transforming energy, no energy is lost. It can not appear or disappear. It can only be converted from one state to another.

2.3 Methods of heat transfer

Heat is an important type of energy. There are three ways to transfer heat: conduction, convection and radiation. Let's examine them.

2.3.1 Conduction

Conduction is the transfer of energy from more energetic particles to less energetic particles. The most important law for conduction is **Fourier's law of heat conduction**. Let's examine a plate with area A, thickness dT and temperature difference dT. The **temperature gradient** is then given by dT/dt. Fourier's law now states that

$$\dot{Q} = -kA\frac{dT}{dt}, \tag{2.3.1}$$

where $\dot{Q}$ is the **heat flow** through the plate. The minus sign in the above equation is a matter of notation. It states that the heat flow is directed opposite to the temperature gradient. (Heat only flows from warm to cold.)

By the way, k is the **thermal conductivity**. It varies (approximately) linearly with the temperature. For gases we have $dk/dT > 0$. (Gases conduct more heat at higher temperatures.) However, for solids and liquids we have $dk/dT < 0$. (Solids and liquids conduct less heat at higher temperatures.)

There are also several other important parameters. First, there is the **thermal diffusivity** α of a material. This is an indication of how fast heat diffuses through the material. It is defined as

$$\alpha = \frac{\text{heat conducted}}{\text{heat stored}} = \frac{k}{\rho c_p}, \tag{2.3.2}$$

where ρ is the **density** and c_p is the **specific heat** of the material. Another important parameter is the **thermal (conduction) resistance** R of a plate with thickness t. It is given by $R = t/k$.

2.3.2 Convection

Convection is the transfer of heat from one part of a fluid/gas to another part, by mixing particles. Convection does not occur in solids.

We can distinguish two kinds of convection. In **free/natural convection**, the particles move because of the heat. (For example, the heat may cause density changes, causing some particles to float upward. This is called **buoyancy**.) In **forced convection**, there are other (external) forces causing the movement of the molecules.

The convection heat flow is given by

$$\dot{Q} = hA\Delta T, \tag{2.3.3}$$

where ΔT is the temperature difference over the plate. Also, h is the **local heat transfor coefficient**. The thermal (convective) resistance is now given by $R = 1/h$.

2.3.3 Radiation

Radiation is the transfer of heat by (usually infra-red) electromagnetic waves. Let's suppose some radiation hits an object. The radiation can then be either **absorbed**, **reflected** or **transmitted**. The

absorptivity α' denotes the part of the radiation that is absorbed. The **reflectivity** ρ' denotes the part that is reflected. And finally, the **transmittivity** τ denotes the part that is transmitted. It is now directly obvious that $\alpha' + \rho' + \tau = 1$.

We define a **black body** to be some hypothetical body with $\rho' = \tau = 0$ and $\alpha' = 1$. In other words, it absorbs all incoming radiation. Similarly, a **white body** has $\alpha' = \tau = 0$ and $\rho' = 1$. It reflects all incoming radiation. Finally, there is the **opaque body**. It has $\tau = 0$ and $\rho' + \alpha' = 1$. All radiation is either absorbed or reflected. Nothing is transmitted.

2.3.4 Applying insulation

Let's suppose we want to isolate a wall. We can put a layer of material, a layer of air and another layer of material. The question is, how much heat does this wall transfer? This question is very easy to solve, if we use the thermal resistances. If we place multiple layers of insulation in series, then we may add up the individual resistances. So,

$$R_{total} = R_1 + R_2 + \ldots + R_n. \tag{2.3.4}$$

The heat flow through the wall is then given by

$$\dot{Q} = -A \frac{\Delta T}{R_{total}}. \tag{2.3.5}$$

2.4 Aviation fuels

One of the industries where sustainability is an issue, is avionics. So let's look at what kind of fuel jet aircraft use.

2.4.1 Fuel properties

When making fuel for jet aircraft, we have the ability to influence certain properties. Important fuel properties include the **maximum freeze point**, the **minimum flash point** (the point at which the fuel mixture is still ignitable), the **clean combustion** possibilities, the **energy density** and the **thermal stability** (how easily the fuel ignites on its own).

Aviation fuel usually consists of hydrocarbons. The chains of carbon atoms have various lengths. The range of these lengths depends on the properties we want to give to our fuel. By using this length, we can already make an important distinction in jet fuel. The so-called **wide-cut** fuels have molecule chains of 5 to 15 carbon atoms in length. The **kerosene** fuels have molecule chains of 8 to 16 carbon atoms in length.

Today, the most often used jet fuels are **Jet A** and **Jet B**. Jet a is a kerosene type fuel. Its maximum freeze point is $-40°C$, while its minimum flash point is $43°C$. On the other hand, Jet B is a wide-cut type fuel. Its maximum freeze point is $-51°$.

2.4.2 Specific energy and energy density

Two very important fuel parameters for the aircraft industry are the specific energy and the energy density. The **specific energy** denotes the amount of energy that can be produced from one kilo of fuel. The **energy density** denotes the amount of energy that can be produced from one liter of fuel.

Both the specific energy and the energy density should be as high as possible. You don't want your fuel to weigh a lot. Nor do you want it to take up a lot of space. (The more space your fuel takes, the bigger and heavier the storage tanks will be.)

One way to compare fuels, is to make a plot out of them. For this, we put 1/energy density on the x axis and 1/specific energy on the y axis. We then mark several fuel types as points in this plot. The closer a fuel type is to the origin, the better it is.

2.4.3 Combustion

Let's look at the way fuel is burned. The chemical reaction is given by

$$C_xH_y + (x + y/4)O_2 \rightarrow x\,CO_2 + y/2\,H_2O + \text{heat}. \tag{2.4.1}$$

So we use fuel and oxygen, to generate CO_2, H_2O and heat. Usually, about $1.25kg$ of H_2O and $3.15kg$ of CO_2 are produced for every kilogram of fuel burned. Next to H_2O and CO_2, the reaction also has byproducts. These byproducts include NO_x, SO_x, **Volatile Organic Compounds** (VOCs) and **Particle Matter** (PM).

An important parameter during combustion, is the **fuel/air (F/A) ratio**. The amount of energy released during the reaction depends on this ratio. There is a certain optimal F/A ratio, giving maximal energy. If the F/A ratio is quite a bit higher than this optimum, then we will have a **fuel rich combustion**. This combustion often results in smoke production. If, however, the F/A ratio is far below the optimum, then there will be a **fuel lean combustion**. This time, the engine has a risk of becoming idle. There will also be a lot of CO and UHC production.

2.4.4 Thermal stability

Another important parameter is the thermal stability of a fuel. When engines can run at high temperatures, they are more efficient. However, we do not want the temperature be too high. In this case, the fuel may ignite spontaneously. And that's not a good thing.

To increase the thermal stability, we need to increase the **breakpoint** of the fuel. (This is the point at which the fuel might start to ignite on its own.) Increasing the breakpoint is mainly done by processing the fuel, and by adding additives.

2.4.5 The Fischer-Tropsch process

The **Fischer-Tropsch process** is a process in which synthetic gas (called **syngas**) is transformed to a liquid fuel. The syngas mainly consists of CO and H_2. The liquid fuel consists of hydrocarbons.

To use the Fischer Tropsch process, we first need syngas. This can be made from many types of fuels. We can make it, for example, from coal. This process consists of three steps. First, there is **pyrolysis**, also known as devolatilization. We remove the volatile components. We remain with a carbon-rich substance called **char**. The second step is **combustion**. The volatile components are burned, to generate heat. This heat is necessary for the the third step, being **gasification**. In this step, we use the char, together with H_2O and O_2, to form CO and H_2. The syngas has been created.

Now that we have syngas, we can perform the Fischer-Tropsch process. The reaction of this process is given by

$$(2n + 1)H_2 + n\,CO \rightarrow C_nH_{2n+2} + n\,H_2O. \tag{2.4.2}$$

For this process, a **catalyst**, like cobalt or iron, is necessary. The resulting liquid (called **parrafin**) is usually distilled, before it is used.

One of the products of this distillation then is **synthetic kerosene**. Synthetic kerosene has several advantages above normal kerosene. Its thermal stability is bigger, and it is cleaner. However, producing synthetic kerosene is, for the moment, still more expensive than simply using normal kerosene.

3. Renewable energy

To save our planet, we should switch to renewable energy sources. These energy sources are, either directly or indirectly, always linked to the sun. We will therefore first examine the sun. After that, we examine some renewable energy sources.

3.1 Using the sun

3.1.1 The working principle of the sun

The **sun** is (like most stars) a sphere of gaseous matter. Its **effective black body temperature** is $T = 5777K$. Its diameter is $d_s = 1.4 \cdot 10^6 km$.

The sun's energy originates from nuclear phusion reactions. Four hydrogen atoms merge to form one helium atom. In a chemical equation, this becomes

$$4 {}_1^1H \Rightarrow {}_2^4 He + \text{energy}. \tag{3.1.1}$$

You may wonder, why does additional energy come out? To find this out, we have to look at the weights of the atoms. A hydrogen atom has a **relative atomic mass** of $1.00797u$. A helium atom weighs $4.0026u$. It follows that about $0.03u$ went 'missing'. This matter was turned into energy, according to Einstein's equation $E = mc^2$. It follows that every reaction gives $26.7MeV$. (By the way, $1eV = 1.602 \cdot 10^{-19}J$.) Since there are a lot of reactions, a lot of energy is produced.

3.1.2 Energy coming from the sun

Due to its high temperature, the sun emits radiation. It does this at various wavelengths λ. The **radiation intensity** (the energy emitted per square meter) is determined by **Plank's radiation law**. This law states that the radiation intensity $E(\lambda, T)$ at a certain wavelength λ, by a body at temperature T, is given by

$$E(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}. \tag{3.1.2}$$

Here, $h = 6.626 \cdot 10^{-34} Js$ is **Plank's constant**, $c = 2.998 \cdot 10^8 m/s$ is the **speed of light** and $k = 1.381 \cdot 10^{-23} J/K$ now is **Boltzmann's constant**. From this equation, we can derive that the sun (with $T \approx 6000K$) emits 48% of its energy in the visible spectrum ($380nm < \lambda < 780nm$). Another 45.6% of the energy is send in the infra-red part of the spectrum ($780nm < \lambda$). The remaining 6.4% is send in the ultra-violet part of the spectrum ($\lambda < 380nm$).

We can also derive the total amount of energy coming from the sun, per square meter. To do this, we have to integrate over all wavelengths λ. Doing this, will give us **Boltzmann's law**. It states that

$$E(T) = \int_0^\infty E(\lambda, T) d\lambda = \sigma T^4, \tag{3.1.3}$$

where $\sigma = 5.670 \cdot 10^{-8} W/m^2K^4$ is still **Stefan's constant**. Also, T is the **black body temperature** (BBT) of the object. There is, however, a slight problem. We usually don't know the BBT. Instead, we know the **surface temperature** T_s. To fix this problem, we use the **emissivity** ε and adjust Boltzmann's law to

$$E(T) = \varepsilon \sigma T_s^4. \tag{3.1.4}$$

3.1.3 Radiation reaching planet Earth

The sun emits a lot of radiation. Outside of Earth's atmosphere, the **intensity** I of this radiation is $I_{sun} = 1367 W/m^2$. The **frontal surface area** A_f of our planet is given by $A_f = \pi R^2$, where $R = 6371 km$ is the **radius of planet Earth**. So, we receive a power from the sun equalling

$$P_{sun} = I_{sun} A_f = I \pi R^2 = 1367 \cdot \pi \cdot \left(6371 \cdot 10^3\right)^2 = 1.74 \cdot 10^{15} W. \tag{3.1.5}$$

From this, we can derive the average radiation we receive on the Earth's surface. The surface area of Earth is $A = 4\pi R^2$. So, on average, we have an intensity of

$$I_{ground,av} = \frac{P_{sun}}{4\pi R^2} = \frac{I}{4} = \frac{1367}{4} = 342 W/m^2. \tag{3.1.6}$$

When this radiation enters the Earth atmosphere, **scattering** occurs. This scattering depends on the **air mass**, which is defined as

$$\text{air mass} = \frac{\text{the distance light travels through the atmosphere}}{\text{the distance if the sun would be directly above you}}. \tag{3.1.7}$$

In space, the air mass is 0. On the equator, when the sun is right above you, the air mass is 1. In general, the air mass depends on the latitude and on the time of day.

3.1.4 The direction of the sun

Many sun-dependent devices (like solar cells and solar boilers) depend on sunlight. So, it might be worth while to keep them directed towards the sun. To find out how we do this, we examine some angles.

- The **slope** β. Imagine a line normal to the solar panel. Also imagine a line normal to the horizontal plane. β is the angle between these two lines.
- The **angle of incidence** θ_i. Imagine a line normal to the solar panel. θ_i is the angle between this line and the position of the sun.
- The **zenith** θ_z. Imagine a line normal to the horizontal plane. θ_z is the angle between this line and the position of the sun. (If $\beta = 0$, then $\theta_i = \theta_z$.)
- The **latitude** φ. The equator has 0° latitude. The North pole is at 90° latitude. And the Netherlands are at about 52° latitude.
- The **declination angle** δ. Let's draw a line between the sun and the Earth. δ is the angle between this line and the equatorial plane. Its value is $\delta = 23.5$ on June 21 and $\delta = -23.5$ on December 21.
- The **surface azimuth angle** γ. Imagine a line normal to the solar panel. Project this line onto the horizontal plane. Now draw another line due South. γ now is the angle between this line, and the projection. (Imagine placing a ball on the solar panel. If it starts rolling South, $\gamma = 0$. If, instead, it rolls North, then $\gamma = 180°$.
- The **argument of perigee** ω. This one is a bit hard to visualize. However, when the sun is at its highest point, then $\omega = 0$. Also, ω linearly depends on time. In 24 hours, it increases by 360°.

From these angles, we can derive an important relation for the incidence angle θ_i. It satisfies

$$\cos\theta_i = (\cos\varphi\cos\beta + \sin\varphi\sin\beta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\beta\sin\gamma + \sin\delta\left(\sin\varphi\cos\beta - \cos\varphi\sin\beta\cos\gamma\right). \tag{3.1.8}$$

This equation can often be simplified, based on known data. Let's mention a few examples. For horizontal surfaces, we have $\beta = 0°$. For vertical surfaces, we have $\beta = 90°$. For surfaces facing South, we have $\gamma = 0°$. If there is sunset, then $\theta_i = 0°$. And so on.

3.2 Solar cells

Perhaps one of the most sustainable ways of getting energy, is by using **solar cells**, also known as **photovoltaic (PV) cells**. But what are they? Let's take a look.

3.2.1 Semiconductors

We can classify materials by their **electrical conductivity** σ. Materials with a conductivity below $10^{-8}\Omega m$ are called **insulators**. Materials with a conductivity above $10^{4}\Omega m$ are called **conductors**. Materials in between are called **semiconductors**. And these semiconductors are necessary to make photovoltaic cells.

Semiconductors have two states: **conducting** and **non-conducting**. Let's examine a semiconductor that is in the non-conducting state. The electrons are then in the so-called **valence band**. We can change the state of the semiconductor to a conducting state. To do this, we emit radiation onto the semiconductor. This radiation causes the electrons to jump to the **conduction band**. They are then free to move and conduct electricity.

The energy required to lift an electron from the valence band to the conduction band is called the **band gap** E_g (also known as the **energy gap**). This jump can be displayed in a **energy band diagram**. In such a diagram, energy levels are denoted by horizontal lines. So there is a horizontal line for the valence band and a horizontal line for the conduction band. The distance between the two lines is thus the band gap.

When an electron has been promoted to the conduction band, it has a tendency to fall back to the valence band. If it does that, it sends out light again. (In fact, it sends out a photon with energy E_g.) However, we want to use the electron to get an electric current. So we need to catch the electron. And that's exactly what is done in solar cells.

3.2.2 The build-up of solar cells

Let's examine the build-up of a photovoltaic cell. Photovoltaic cells are made out of semiconductors, which are mostly made from silicon. Silicon has four so-called **valence electrons** (electrons that can be used to conduct electricity). However, solar cells aren't made up out of pure silicon. Instead, the silicon has been given impurities. (This is called **doping**.)

We can add different types of impurities. We can add atoms with five valence electrons (like **phosphorus**). The surplus of free electrons results in a **n-type** semiconductor. (The n stands for negative.) We can also add atoms with three valence electrons (like **boron**). We thus have a shortage of free electrons, or, similarly, a surplus of **holes**. This gives us a **p-type** semiconductor. (You can guess what the p stands for.)

Now let's build a photovoltaic cell. For this, we start with a thick p-type layer. (With thick, we mean several nanometers.) We put a thin n-type layer on top of this. The surface between the two layers is known as the **junction**. We also connect the two layers. To do this, we add **front** and **rear metal contacts**. These are connected by a conducting wire, called a **current collector**.

Now let's examine the working principle. A photon hits the photovoltaic cell. This usually occurs near the junction. This photon promotes an electron to the conduction band, leaving a hole. The hole moves down towards the p-type layer. (This is because, in p-type layers, a surplus of holes is normal.) Similarly, the free electron tends to move up towards the n-type layer. After the electron has passed through the n-type layer, it goes into one of the front metal contacts. It goes through the current collector to the rear metal contact, at the back of the p-type layer. At this point, the electron recombines with the hole.

3.2.3 Improving solar cells

Solar cells don't have a 100% efficiency. There are several reasons for this. First of all, not all radiation reaches the semiconductors. The front metal contacts may be in the way. And part of the light is not absorped but reflected.

However, also the energy E of the incoming photons is important. To promote an electron from the valence band to the conduction band, we would like to have a photon whose energy E equals the band gap E_g. If the photon has less energy ($E < E_g$), it simply passes through the semiconductor. If the photon has more energy ($E > E_g$), it will promote the electron. However, the remaining energy $E - E_g$ is lost as heat.

To increase the efficiency, we can use cells of multiple layers. These are so-called **multi-junction PV cells**. In such a cell, there are multiple n-type and p-type layers. However, every set of layers has a different band gap. Every layer thus uses photons with different amounts of energy. In this way, photons with a varying range of energies can be efficiently transformed to a current.

3.2.4 Using solar cells

A solar cells gives electricity. This electricity has a certain **current** I and a **voltage** V. (Don't confuse the current I with the intensity I.) We can plot these against each other. We then place V on the horizontal axis and I on the vertical axis. The voltage at $I = 0$ is called the **open circuit voltage**. Similarly, the current at $V = 0$ is called the **short circuit voltage**.

When using solar cells, we want to get a maximum amount of power. The **power** P is given by $P = IV$. The point at which maximum power is achieved is called the **maximum power point** (MMP). To find it, an electrical device called a **maximum power point tracker** can be used.

Let's suppose we have n PV cells. These cells give a current I_{cell} and a voltage V_{cell}. We can connect these cells either in series, or in parallel. If we put them in **series**, then

$$I_{series} = I_{cell} \qquad \text{and} \qquad V_{series} = nV_{cell}. \tag{3.2.1}$$

In other words, we add up the voltages. When we put them in parallel, the situation is different. In this case, we need to add up the currents. So,

$$I_{parallel} = nI_{cell} \qquad \text{and} \qquad V_{parallel} = V_{cell}. \tag{3.2.2}$$

3.3 Biomass

3.3.1 Basic biomass theory

Biomass is the general term for (former) living matter. Examples are wood, plants, manure and algae. Theoretically, fossile fuels are also biomass, although they are usually not considered as such. Energy derived from biomass is called **bioenergy**.

To create biomass, sunlight is needed. This ligt is then converted to biomass, by the process called **photosynthesis**. The (simplified) reaction is given by

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2. \tag{3.3.1}$$

The molecule $C_6H_{12}O_6$ is known as **glucose**. The amount of light necessary for the above reaction is $2.81MJ/mole$. The efficiency of the reaction is very low: less than 1%.

3.3.2 A calculation example

Let's do a calculation example for biomass. Let's examine 1 square meter of biomass, for one year. The average intensity on earth is $I_{ground,av} = 342 W/m^2$. So, for one square meter, in one year, we will have an energy

$$E_{incoming} = 342 \cdot 365.25 \cdot 24 \cdot 60 \cdot 60 = 1.079 \cdot 10^{10} J/m^2 y. \tag{3.3.2}$$

Now let's look at how much energy we need to create biomass. Photosynthesis requires $2.81 MJ/mole$. $1 mole$ of glucose weighs $180g$. (C has an atomic weight of 12, H has a weight of 1 and O weights 16.) The amount of energy needed, to create $1kg$ of biomass, is thus

$$E_{biomass} = \frac{2.81 \cdot 10^6}{180 \cdot 10^{-3}} = 15.61 \cdot 10^6 J = 15.61 MJ/kg. \tag{3.3.3}$$

We can't equate the incoming radiation directly. This is because there is also an **albedo** (a sort of effective reflectiveness) of 30%. (So only 70% is absorped.) Also, the reaction has an efficiency of (assumed) 0.7%. The amount of biomass created is thus

$$m_{biomass} = \frac{1.079 \cdot 10^{10}}{15.61 \cdot 10^6} \cdot 0.7 \cdot 0.007 = 3.387 kg/m^2 y. \tag{3.3.4}$$

Of course this amount differs per crop type. But it's still not particularly much. If we have plenty of space, then using biomass could be a cheap solution. But if we want to have a higher gain per area, we'd better use another option, like solar cells.

4. Projects for a better Earth

There are several projects and ideas that try to improve our world. Let's take a look at some of them.

4.1 Sustainable ideas

4.1.1 Cradle to cradle

A normal trend in sustainable thinking, is to reduce the amount of waste. In the **cradle to cradle** (C2C) ideology, things are done differently. It is attempted to create only waste that can be used in other products as well. A very important in C2C thinking is **waste equals food**. By applying C2C methods, we should make our footprint on our environment smaller, or even negative. We should work with nature, rather than against.

How should we implement C2C? It depends on the kind of product. For biological products, we should create a **bio-cycle**: The waste should be used as food by something else. For technological products, we should create a **techno-cycle**: We have to recycle the parts that can not be put back into nature. To accomplish this, it is wise to make products return to the producer. It is the duty of the producer to recycle the parts. This will make producers use parts that are more easy to recycle. The risk of the products to the environment are therefore not taken by the society anymore. Instead, they are taken by the producers.

4.1.2 Feed in system

A **feed in system** is a system that can be used to enlarge the market for a new technology. Once the market is large, the production costs will be lower. The feed in system is a concept succesfully applied in Germany to introduce solar energy. We'll examine this system by examining what was done in Germany.

In Germany, in 1995, the government ensured that people, putting solar panels on their roof, would get $1€/kWh$ for the next 20 years. The government got this money from the people not getting the solar panels. (The plan was thus cost-neutral for the government.) Due to this promise, quite some people put solar panels on their roof. On the long run, they made a slight profit. The people not involved in the project payed a little. But, since there were a lot more people out of the project than in it, they didn't have to pay much. So they hardly noticed it.

In 2005, due to higher production rates, the price of solar panels had been reduced. So now the government promised $0.65€/kWh$ for the next 20 years. More people started getting solar panels. So the group of people that was not in the project (and that are effectively paying for it) got smaller. However, the costs of the project also became lower. So, the people didn't have to start paying more.

This process continues, until the solar panels become a viable alternative to normal electric energy. By this time, the market for solar cells has become large enough to sustain itself.

We have just shown one way in which the feed in system can be applied. Of course, it can be applied in other situations as well. It could, for example, be used for the introduction of electric cars. (We'll discuss electric cars later.)

4.2 Making cars sustainable

Cars take up a lot of energy. They cause a big part of our climate problems. Making them sustainable would be a massive step forward to a sustainable planet. But how can we make cars sustainable?

4.2.1 Electric cars

Let's examine a car. An average car drives about $15000 km/y$. It uses $1l$ of fuel for every $15km$ driven. So in one year, a car uses $1000l$ of fuel. Fuel costs about $1.5€/l$. So, driving for one year on fossile fuels costs €1500.

However, we can also let a car run on electricity. A car needs about $1kWh$ of electricity for a distance of $10km$. So in one year, a car needs $1500kWh$ of electricity. Electricity costs something like $20cts/kWh$. So driving for one year now only costs 300 euros.

Driving on electricity is thus meach cheaper. This is mainly caused by a difference in efficiency. When burning fossile fuels, our engine only has an efficiency of about 15%. However, when using electricity, we have an efficiency of 90%. That saves a lot!

Let's consider an idea: we put solar panels on our garage. These solar panels then power our car. In this case, electricity is a bit more expensive. It now costs something like $35cts/kWh$. So driving for one year costs 525 euros. It's still a lot cheaper than using fossile fuels. So, let's all use electric cars!

4.2.2 Vehicle to grid

Conventional power plants have a big downside. They can only generate a constant amount of power. (Starting up a power plant usually takes a week.) But the demand for power is not constant. The demand during the day is much higher than the demand during the night. So, power needs to be stored. This is usually rather difficult and expensive.

But now let's suppose that all cars are electrically driven. The batteries of these cars can be used for storage. Let's examine such a battery. If a car needs to drive $200km$ on one tank, then it needs a capacity of $20kWh$. If we use **lead acid** batteries, with specific capacity $0.03kWh/kg$, then we have $700kg$ of batteries. But if we use **lithium polymer** batteries, with specific capacity $0.2kWh/kg$, then we only have $100kg$ of batteries. That's good enough to put in a car.

Now let's look at what we need to store. An average household uses $4000kWh/y \approx 0.5kW$. This means that a car can store for about 40 hours worth of electricity. That's sufficient for a household to get through the day. So, if we connect cars to the electricity grid, then the whole energy storage problem is more or less solved. By the way, this idea, of connecting cars to the electricity grid, is called **vehicle to grid** (V2G).

4.2.3 Using hydrogen as fuel

We can also let cars drive on hydrogen. Hydrogen can contain much more energy than fossile fuels. (Burning $1kg$ of hydrogen (H_2) gives 8 times more energy than burning $1kg$ of methane (CH_4).) Plus, converting hydrogen to electricity can be done with an efficiency of 50% to 70%, where this is only about 15% for fossil fuels.

Hydrogen is positive in many other ways too. Hydrogen is sufficiently available on our planet. The world production of hydrogen is already quite big ($50MT/y$), and it's expected to rise in the coming years. Hydrogen cars aren't dangerous, as many people believe. Instead, normal fuels are more dangerous to use than hydrogen. Fuel cells are also very safe. They are silent, and hardly have moving parts, so they require few maintenance.

4.3 Contests

Several contests are being held, aiming to promote sustainable thinking. These contests also often result in interesting new developments. Let's take a look at some of these contests.

4.3.1 The World Solar Challenge

The **World Solar Challenge** (WSC) is held every two years in Australia. It is a race of over $3000km$. Teams drive from eight o'clock in the morning to five o'clock in the afternoon.

In 2001, the Nuna 1 participated. First, we'll examine the **roll drag** of this car. Its mass was $m = 350kg$. The weight was thus $W = 3500N$. With a friction coefficient of $\mu_k = 0.01$, the roll drag was only $D = \mu_k N = \mu_k W = 35N$. With a velocity of $30m/s$, this gave a power of $P_{roll} = 1000W$.

Now, let's examine **aerodynamic drag**. The frontal surface area was $S_{front} = 1.1m^2$. The drag coefficient was $C_D = 0.1$. So, the effective drag surface was $S_d = C_D S_{front} \approx 0.1m^2$. The dynamic pressure was $\frac{1}{2}\rho V^2 \approx 500Pa$. The power necessary to compensate for the aerodynamic drag thus is $P_{aero} = 1500W$. In reality, the Nuna team managed to lower these figures even further, to $P_{roll} = 700W$ and $P_{aero} = 1400W$. So, $P_{total} = 2100W$.

To generate power, solar cells were used. A surface area of $S = 9m^2$ was used. The solar cells had an efficiency of $\eta = 24\%$. In Australia, during the summer, the average solar intensity is about $I = 1000W/m^2$. This thus gave a power production of $P_{prod} = 2160W/m^2$. There is therefore sufficient production of energy to power the car.

The newest Nuna, the Nuna 5, will get an efficiency of roughly $\eta = 35\%$. Also, its drag coefficient will be a lot lower. So we can expect great things from this new solar car.

4.3.2 Fryslan Sinneboat Race

The **Fryslan Sinneboat Race** (Frisian for Frisian Solarboat Race) is a race for solar boats. It's also held once every two years. In 2006, the first edition was held. A team from Delft won, having an average speed of $13km/h$. In 2008, Delft won again. This time the speed was $20km/h$. And the plans for 2010 are even more ambitious.

4.4 Other projects

There are several other projects, which may potentially improve our planet. Let's examine a few.

4.4.1 Sailing boat

Let's examine a sailing boat. We could put something like an inverse propeller on this boat. Normally, a propeller uses energy and propels the boat. The inverse propeller does the opposite: it provides energy. In this way, two persons can live on the boat. And, to have enough energy, they only have to sail one day per week.

Let's do some calculations. We say that the boat has $S = 30m^2$ of sail. The wind speed is $V_w = 10m/s$ on average. The dynamic pressure is thus $q = \frac{1}{2}\rho V_w^2 \approx 60Pa$. We thus have a force of $F = qS = 18kN$. The boat usually sails at a speed of $V_b = 4m/s$. So, the available power is $P = FV_b = 72kW$. Assuming that the inverse propeller has an efficiency of 10%, the battery receives $7kW$ of power. If the battery has a capacity of $350kWh$, then we only need to sail 50 hours (2 days) to fill the batteries.

Now let's look at how much power we need. An average household uses $4000kWh/y \approx 0.5kW$. Let's say that the boat, including equipment, uses twice this amount, being $1kWh$. We can thus use our battery without sailing for 350 hours, which is over two weeks.

Let's examine the costs. The sail costs about 10.000 euros. It lasts for two years, which equals about 17000 hours. The sail costs thus are $0.6€/h$. When sailing, we generate $7kW = 7kWh/h$. So, our energy costs $0.6/7 \approx 0.1€/kWh$. Of course the other equipment has to be taken into account as well. But still, it's quite a good price for electricity.

4.4.2 The Superbus

The **Superbus** is a new kind of bus that is still in development. It will be powered by batteries. It is supposed to be driving on its own lanes called Super Lanes. Building these Super Lanes (the infrastructure) is rather expensive. But it is still less expensive than building rails. So the Superbus could, in time, be a viable alternative for replacing trains.

The superbus will be travelling at velocities between $150km/h$ and $250km/h$ outside of cities. Because of its unique aerodynamic shape, and its low position above the road, it is aerodynamically very efficient. Due to this, not much power will be needed for propulsion. The Superbus is thus an economically feasible project.

4.4.3 The Laddermill

When you hold up a kite against the wind, it tends to go up. But, when you have an aircraft in the air, it tends to come down. These principles are used in a **laddermill**. A laddermill consists of a chain kites.

Let's consider one such kite. Its area will be about $10m^2$. Its cost is around 30 euros, when it is fabricated in China. The power provided by the kite is between $3kW$ and $5kW$. The cloth of the kites lasts for about $500h$. So a kite generates at least $1500kWh$. This implies that the cost of electricity, coming from the laddermill, is about $30/1500 = 0.02€/kWh$. This is very cheap for electricity. Of course there are several other operational costs. But still, the laddermill seems to be a viable way of generating cheap electricity.

4.4.4 Solar cells on the Afsluitdijk

In the North of the Netherlands is a $30km$ long dike, called the **Afsluitdijk**. We can put solar cells on it. The height of the dike is about $6m$. We thus have a surface area of $180000m^2$. Fixed solar panels in the Netherlands usually give an energy of about $110kWh/m^2y$. The whole Afsluitdijk can thus provide us with $55000kWh$ every day.

Now let's look at the cars driving over the Afsluitdijk. There are 18000 of them every day. If these cars would have been electric, each one would have needed $3kWh$ to cross the afsluidijk. So all cars together would need $54000kWh$. The solar panels on the Afsluitdijk could then provide power for all the cars driving over it. Isn't that amazing?