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.

1 Using the sun

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

$$4_1^1H \Rightarrow_2^4 He + \text{energy}. \tag{1.1}$$

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.

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

$$E(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}. \tag{1.2}$$

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

$$E(T) = \int_0^\infty E(\lambda, T) d\lambda = \sigma T^4, \tag{1.3}$$

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

$$E(T) = \varepsilon \sigma T_s^4. \tag{1.4}$$

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

$$P_{sun} = I_{sun} A_f = I \pi R^2 = 1367 \cdot \pi \cdot \left(6371 \cdot 10^3\right)^2 = 1.74 \cdot 10^{15} W. \tag{1.5}$$

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

$$I_{ground,av} = \frac{P_{sun}}{4\pi R^2} = \frac{I}{4} = \frac{1367}{4} = 342 W/m^2. \tag{1.6}$$

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

$$\text{air mass} = \frac{\text{the distance light travels through the atmosphere}}{\text{the distance if the sun would be directly above you}}. \tag{1.7}$$

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.

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

$$\cos\theta_i = (\cos\varphi\cos\beta + \sin\varphi\sin\beta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\beta\sin\gamma + \sin\delta\left(\sin\varphi\cos\beta - \cos\varphi\sin\beta\cos\gamma\right). \tag{1.8}$$

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.

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.

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.

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.

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 absorbed 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.

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

$$I_{series} = I_{cell} \qquad \text{and} \qquad V_{series} = nV_{cell}. \tag{2.1}$$

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,

$$I_{parallel} = nI_{cell} \qquad \text{and} \qquad V_{parallel} = V_{cell}. \tag{2.2}$$

3 Biomass

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

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2. \tag{3.1}$$

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

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 $I_{ground,av} = 342W/m^2$. So, for one square meter, in one year, we will have an energy

$$E_{incoming} = 342 \cdot 365.25 \cdot 24 \cdot 60 \cdot 60 = 1.079 \cdot 10^{10} J/m^2 y. \tag{3.2}$$

Now let's look at how much energy we need to create biomass. Photosynthesis requires $2.81MJ/mole$. $1mole$ 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

$$E_{biomass} = \frac{2.81 \cdot 10^6}{180 \cdot 10^{-3}} = 15.61 \cdot 10^6 J = 15.61MJ/kg. \tag{3.3}$$

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

$$m_{biomass} = \frac{1.079 \cdot 10^{10}}{15.61 \cdot 10^6} \cdot 0.7 \cdot 0.007 = 3.387 kg/m^2 y. \tag{3.4}$$

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.