ZERO-ENERGY DESIGN

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ANDY VAN DEN DOBBELSTEEN

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Zero-Energy Design

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Andy van den Dobbelsteen (main author and editor)

With contributions by:
Eric van den Ham
Tess Blom
Sabine Jansen
Regina Bokel
Siebe Broersma
Leo Gommans
Michiel Fremouw

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Preface

This book should have come earlier. Considering the climate crisis and the rapid sustainable transition needed in our way of living, our society, and our built environment, attaining net zero-energy buildings has become as urgent as ever. Every building constructed at the moment should pose no burden on our future and especially not on that of our children and grandchildren's future. Nonetheless, every day I still see new projects arise that are not energy-producing, neither circular, nor nature-inclusive. In my opinion, that is an enormous waste of potential. This book is meant to help the sustainable design process of buildings, primarily focused on making them energy-neutral or better.

If newly constructed buildings are not sustainable – defined by my master Jón Kristinsson as something future generations want to inherit, use and maintain – what can be done about the existing building stock? Making older buildings energy-neutral might be difficult, if not impossible, but there are plenty of examples across the world that demonstrate it is possible. And existing buildings have one great environmental advantage over (demolition and) newly built ones: the largest part of their embodied carbon was already invested in the past and no longer contributes to aggravated climate change.

So, energy renovations and transformations are very important. Complicated but important. Therefore, an approach to making these buildings net zero-energy is perhaps even more important, especially considering that most real estate in the future has already been built today. This book is meant to help in the redesign of existing buildings, proposing a stepped approach that brings structure in the process that still allows for creativity. A lot of creativity, if you ask me. The book will exemplify this by means of many cases of zero-energy designs.

Zero-Energy Design is based on our eponymous massive open online course (MOOC, free of charge) and professional education course (ProfEd) offered by TU Delft via Edx Online (https://www.edx.org/school/delftx). Edx Online voted it the best online course of 2020. In the same year the MOOC's mini-film called Energy Slaves won a 'Gouden Reiger' (Gold Heron, the Dutch Oscar for commissioned films. Now this is all vanity, but it demonstrated the need for a textual elaboration of the courses' and film's content, which due to various reasons came later than anticipated. But here it is, finally.

So, this book should have come earlier, but I hope it will help you, dear reader, in your endeavours to design or redesign, to retrofit or refurbish any building that you are working on. And that together we can contribute to a sustainable built environment of the future.

Wishing you wisdom and pleasure in reading Zero-Energy Design,

Spring 2021, Andy van den Dobbelsteen

Inhoud

1 GETTING STARTED

Roofscape in Venice, Italy [photo: Andy van den Dobbelsteen]

1.1 Introduction

BY ANDY VAN DEN DOBBELSTEEN

1.1.1 Challenges

Challenges for the future

The reason why designing zero-energy buildings is important starts with the planet we live on, the only planet we know that is inhabitable (figure 1.1). Its liveable atmosphere is very thin: comparable to a thin foil around a football.
As humans, we are seriously disturbing the earth and endangering our own future, or at least that of future generations.

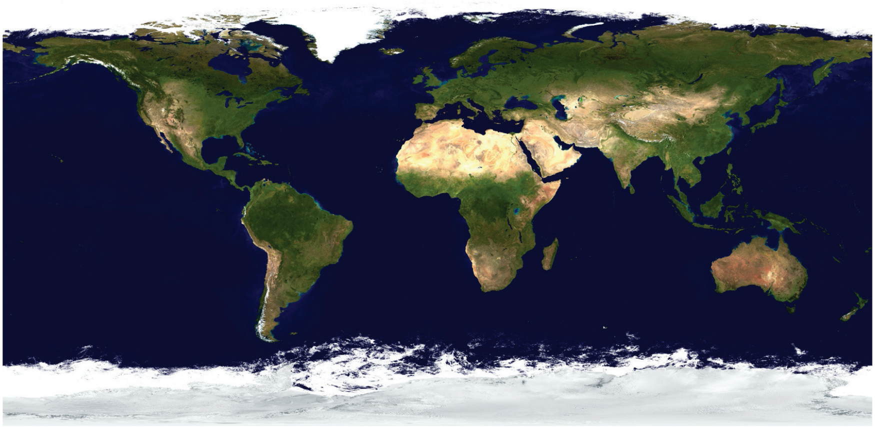


Figure 1.1 Composite satellite image of the world, plate Carrée projection [Wikipedia, public domain]

Therefore, in contrast to the generations of planners, architects, and engineers before us, we have to face and solve three great sustainability challenges in our work.
The first is climate change: it is happening already, and we cannot stop what our parents and grandparents have caused. For this reason, we have to be prepared for extreme weather events.
Secondly, depletion of fossil fuels is a challenge: at our present level of consumption, we might postpone the end of the Fossil Era by another human lifespan, but there will be an end to it regardless. Moreover, if we want to avoid extreme climate events, we must switch to clean renewables completely.
Furthermore, scarcity of other resources is an issue: many resources are being depleted, such as the rare earth metals required for electronics, batteries, and renewable energy devices. The only way to solve this is to become entirely circular in our material use.

This book mainly focuses on a net zero-energy and carbon-neutral built environment, and indirectly focuses on avoiding excessive climate change.

Climate Change

Though it is increasingly rare, sometimes a discussion still pops up about the truth of climate change and the influence of carbon emissions and humans on it. This book is not going into that debate in any great depth, but we want to clarify that modern climate science (as collected, interpreted, and presented by the International Panel on Climate Change (IPCC) [IPCC 2014; new report coming up in 2021], representing thousands of climate scientists, is very clear about the following:

– The climate is changing more rapidly than ever before.
– Natural causes and geological cycles cannot explain this quick change.
– With a 'probability bordering certainty' (95%), the aggravated climate change is caused by greenhouse gases, mostly emitted through human processes.

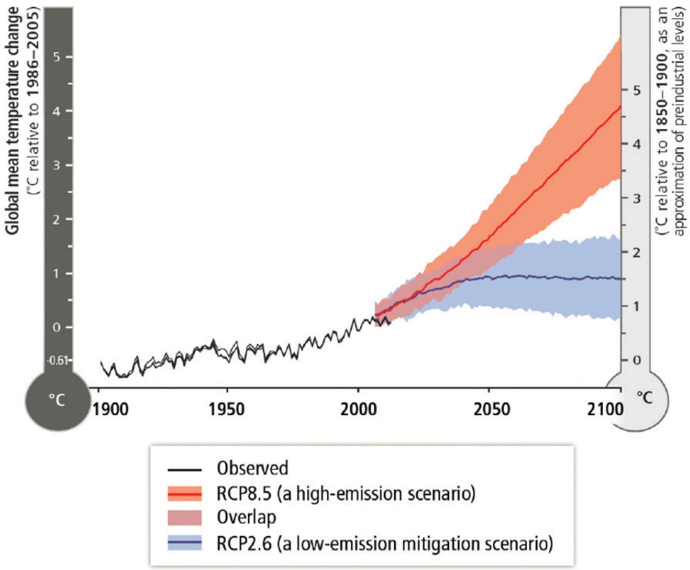


Figure 1.2 Expected global mean temperature increase, under different scenarios [IPCC 2014]

Estimates vary, but depending on the action taken or not taken, within this century the temperature on earth will most probably rise between 1.5 and 5 degrees (figure 1.2). All scenarios will have consequences, some very severe. Therefore, it is not for no reason that climate scientists call for urgent action.

Vulnerability

There is another reason why we should shift away from our current centralised, fossil-fuel-based energy system: vulnerability.

Figure 1.3 News items about disturbances in the delivery of energy [New York Times, NRC, Independent]

Over the last few decades many urbanised areas have experienced a disturbance in the supply of energy, resulting either from natural, technical or political causes (figure 1.3).
If we want to create a resilient society, our cities must become more self-sufficient.

Inequality

There is an important social reason for energy neutrality too. Figure 1.4 is a map showing the size of countries in the world if they had to produce all resources themselves. At present, the earth's resources are neither divided equally nor are they managed sustainably. It is the duty of the westernised world to come up with solutions that can also help developing and emerging economies.

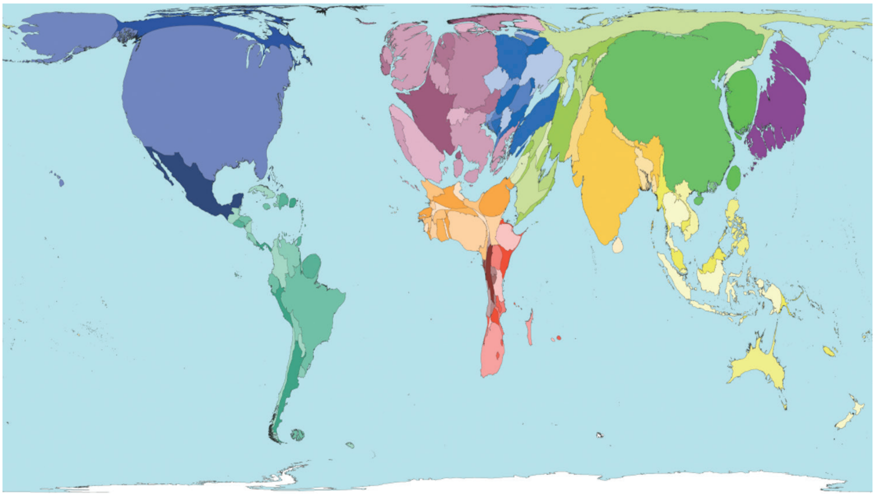


Figure 1.4 Ecological Footprint of all countries in the world [www.worldmapper.org, kind permission to use]

The Paris Agreements and the built environment

It is for these reasons, but especially because of severe climate change, that the Paris Agreements were signed by around 150 countries. The implication is that carbon emissions must be reduced, necessitating a rapid energy transition to clean renewables.

The built environment is an important factor therein, because it uses 30 to 40% of all energy. It needs to become carbon neutral by 2050. In order to achieve this goal, we need to learn how to design net zero-energy buildings, and also how to make existing buildings energy neutral.

1.1.2 This book

In this book you will learn
- how to analyse the energy use of a building,
- how to analyse the local climate and select appropriate measures,
- how to use a stepped approach to find the right energy measures,
- how to develop a net zero-energy concept for a building,
- how to calculate your design's energy performance.

Example

A zero-energy concept could look like figure 1.5: a scheme that explains the energy and climate system for the building. This scheme will be explained further in the book.

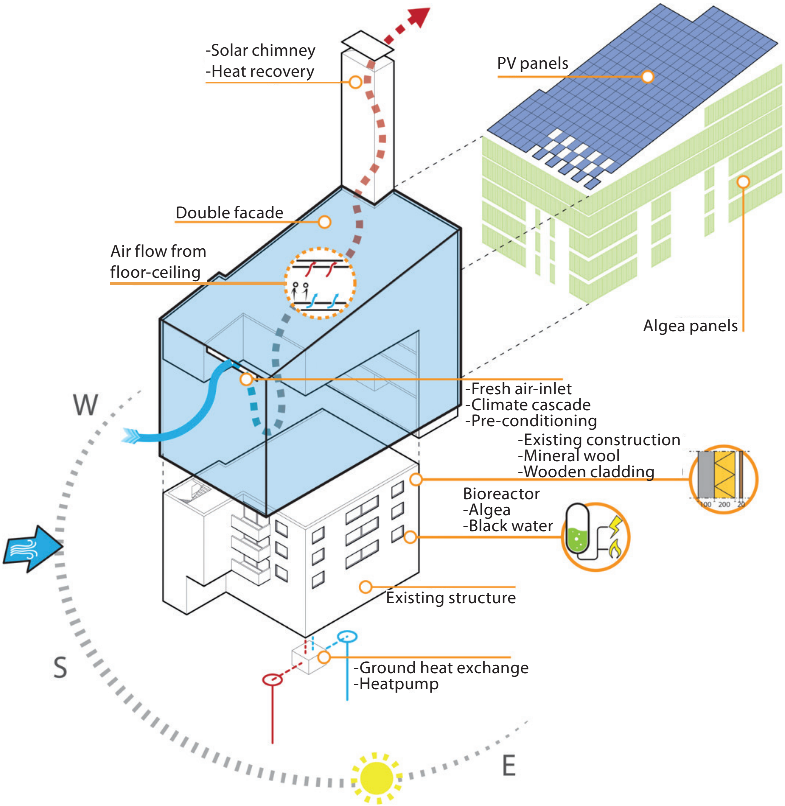


Figure 1.5 Zero-energy design example [Sacha Noorlander, Iris van den Brink, Maya de Groot, 2015]

Definition

There are different definitions related to zero-energy building design.
One can talk of 'energy neutral', 'zero energy', or 'net zero energy'. In the Netherlands, the term 'zero on the meter' is also well-known, indicating that over a year's time there are no energy costs.

We define a zero-energy building as follows:

> *A building that generates all energy it uses during one year's time entirely from renewable sources.*

New Stepped Strategy

The design approach used in this book is called the New Stepped Strategy, which is depicted in the sketch of figure 1.6.

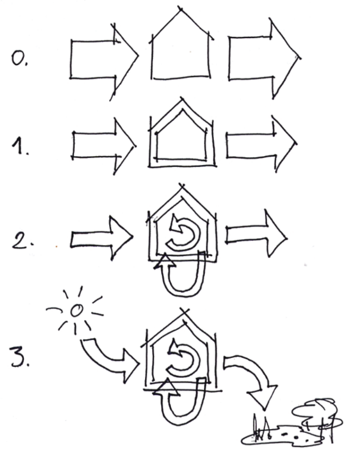


Figure 1.6 Graphic depiction of the New Stepped Strategy [Dobbelsteen, 2008]

0. **Research**
   It starts with a proper study of the local circumstances.
1. **Reduce**
   We then look at means to reduce the energy demand, by means of passive, smart bioclimatic design, and through energy-efficient appliances.
2. **Reuse**
   There is a lot of residual energy in air, water, and material, which can often be recovered for use in the building. So, the next step is to make use of these waste flows.
3. **Produce**
   The final step is to generate the remaining demand from renewable energy sources. If there is 'waste' remaining it should not further disturb the environment, but be used as food or a resource for other processes, as was clarified in the Cradle to Cradle theory [McDonough & Braungart 2002].

Outline

You can find the outline of this book in figure 1.7. This figure depicts the chapters, which follow the steps of the approach and which will convey essential knowledge.

1	Film: **Energy Slaves**	**Getting started**
2	Documentary: **Prêt-à-Loger**	**Researching the local circumstances**
3	Documentary: **Proyecto Roble**	**Reducing the energy demand**
4	Documentary: **Villa Flora**	**Using residual energy**
5	Documentary: **Pulse**	**Generating renewable energy**
6	Documentary: **MOR**	**Integrating it all**

Figure 1.7 Outline of this book and accompanying films

Five chapters are accompanied by a case study of a net zero-energy building (figure 1.8), about which a short documentary was made.

You can find these documentaries on the website accompanying this book.

Figure 1.8 Buildings featured in our mini-documentaries 'Energy Slaves' [photos: Andy van den Dobbelsteen]

We recommend having these documentaries preceded by a short prize-winning film called ‘Energy Slaves’ (figure 1.9), about the energy use of a common household in the Netherlands, in north-western Europe.

Figure 1.9 Filmset images of Energy Slaves [photos: Andy van den Dobbelsteen]

Please watch Energy Slaves on the website. The voice-over is in English and you can select English subtitles for the acted scenes in Dutch.

1.2 Energy & Power

BY ANDY VAN DEN DOBBELSTEEN

1.2.1 Energy Slaves

If you have watched the Energy Slaves film, you might think that every household needs slaves to produce its energy, but that was simply a humorous way of clarifying the quantity of energy and power required to run a household. It is commonly fossil fuels that provide the domestic energy required. The film demonstrates that this amount of energy is immense and difficult to supply with human power alone. We would need many rowers to keep us going. You might have learnt that some activities require more power than others, and that some activities last longer than others. Together, power and duration define the energy used.
You might have also noticed that a substantial amount of the energy a house uses is often hidden and unknown. For instance, one rower had to work all night, in order to keep some appliances and building services going. Leaving equipment on, or on stand-by, still demands electricity, around 10% of the total energy use.

In order to understand these mechanisms better, this section will introduce energy and power. Therefore, we have to go back to school, to recollect some fundamental knowledge.

1.2.2 Energy

Units of energy

The official unit for energy – as agreed in the Système Internationale d'Unités (SI) – is the joule. Other magnitudes of energy are expressed as follows.

J	joule		
kJ	kilojoule	10^3 J	1,000 J
MJ	megajoule	10^6 J	1,000,000 J
GJ	gigajoule	10^9 J	1,000,000,000 J
TJ	terajoule	10^{12} J	1,000,000,000,000 J
PJ	petajoule	10^{15} J	1,000,000,000,000,000 J
EJ	exajoule	10^{18} J	1,000,000,000,000,000,000 J

The exajoule is the largest order of magnitude on planet earth. When looking at buildings, megajoules and gigajoules are the most common units.

Other units used for energy are shown below. The latter is what you usually see on food packaging. People commonly talk of 'calories' when indicating the energy content of food, but they actually mean 'kilocalories'.

cal	calorie	4.19 J
kcal	kilocalorie	4.19 kJ

Energy units commonly used for electricity are based on watt-hours, as we can see below.

Wh	watt-hour	3.6 kJ
kWh	kilowatt-hour	3.6 MJ
GWh	gigawatt-hour	3.6 GJ

The kilowatt-hour is the common unit for electricity use in buildings.

Conversion

What is important to remember, however, are these conversions:

1 kWh equals 3.6 MJ
or
1 MJ equals 0.278 kWh.

You will need these later when we do energy conversions, especially between heat (commonly given in megajoules) and electricity (given in kilowatt-hours).

Energetic value of fossil fuels

When we study fossil fuels, we see the following energy content per typical SI quantity.

Natural gas	1 m^3	35.2 MJ	(9.8 kWh)
Petrol	1 l	32.4 MJ	(9.0 kWh)
Diesel	1 l	35.8 MJ	(10.0 kWh)
Kerosine	1 l	37.4 MJ	(10.4 kWh)
Oil and fat (vegetable/animal)	1 kg	37.0 MJ	(10.3 kWh)
LPG	1 m^3	26.0 MJ	(7.2 kWh)
Coal	1 kg	24.0 MJ	(6.7 kWh)
Wood	1 kg	20.0 MJ	(5.6 kWh)

If you look carefully at the energy value of natural gas, petrol, diesel, kerosene or vegetable oils and fats, you will see a common denominator: they all revolve around 36 MJ, or 10 kWh (36 MJ = 36*0.278 kWh = 10 kWh), as we know from the conversion factor.
LPG – liquefied petrol gas – and coal have a smaller energy content: they only contain around 25 megajoules of energy. And wood, though not a fossil fuel, contains 20 megajoules per kilogram.

1.2.3 Power

Units of power

Power is the energy used or produced over a certain period. Therefore, its logical unit is joule per second (J/s), for which we use the term watt (W). Just as with energy, power can be given different magnitudes.

W	watt	1 J/s
kW	kilowatt	10^3 W or J/s
MW	megawatt	10^6 W or J/s
GW	gigawatt	10^9 W or J/s
TW	terawatt	10^{12} W or J/s
PW	petawatt	10^{15} W or J/s

For buildings, kilowatt and megawatt are the most common units.

In his time, the Scottish engineer James Watt, after whom the unit of power was eventually named, originally used a different unit for power: the horsepower.

hp	horsepower	746 W[1]

This quantification suggests that one horse can deliver 746 watts of power. A work horse is usually stronger than that, but as was agreed, this is the conversion value.

Human activities

Below is an overview of typical values of power for human activities.

Sleeping	75 W
Sitting	100 W[2]
Walking	230 W
Race walking	345 W
Cycling	475 W
Swimming	550 W
Running	670 W
Judo	1150 W

As you can see, we all use energy, even when asleep. Just sitting behind your screen, you already use just around 100 watts. Judo (or wrestling) is physically

1 In German, the unit PS (Pferdestarke), and in Dutch, PK (paardekracht), mean the same as horse power (hp), but they have a slightly different quantity: 1 PS or PK = 0.986 hp = 736 W.

2 This is an average value. It is related to the unit 'metabolism' (met). According to EN-ISO 7730-2005 (Appendix B), 1 met = 58 W/m^2; multiplying this by a human's body surface defines the power. 58 W/m^2 * 1.8 m^2 for an average male = 104 W.

and energetically one of the sports that demands the most power, ten times more power than sitting. Not all of this power, however, is put into force and motion: most of the 1150 watts is emitted as heat.
The rowers we saw in the Energy Slaves film produced up to 350 watts, but in total it must have been at least twice as much, contributing to the warming of the basement where the rowers were situated.

Equipment

Below you see the power of some forms of equipment.

Lamp		1 – 100 W
Computer		200 – 300 W
Television		100 – 120 W
Vacuum cleaner		1200 – 1800 W
Small car	80 hp	60000 W
Big car	120 hp	90000 W
Sports car	500 hp	375000 W

Through LED technology, lighting has become up to 95% more efficient compared to old-fashioned light bulbs. Bear in mind that a normal car requires quite a lot of power: about 100 horses! You might start to look at sports cars differently, understanding the enormous power they demand.

1.2.4 The flame and energy used at home

The powerful flame

To get an even better understanding of energy, it is useful to understand the power of the flame, a lesson that professors Taeke de Jong and Jo Hermans taught me.

There is something magical around the value of 100 watts. We already saw that a human being at rest uses and produces around 100 watts of power. The common old-fashioned lightbulb's power was 100 W. Moreover, the power of one flame – either from a candle, from wood or from gas – is always around 100 watts. If a flame burns for one hour, it will have produced one 100 watts x 1 hour, which is 100 watt-hours, or 0.1 kilowatt-hour, or 0.36 megajoule.

The energy of taking a shower

Now let us see why in the 'Energy Slaves' film taking a shower demanded so much power. We first need to know the power of a hot water boiler. Old boilers or geysers often had 10 times 10 flames heating a pipe of water. This means the power of such a boiler or geyser is 10 x 10 x 100 watts, which is 10,000 watts or 10 kilowatts.
The film demonstrated that this requires about thirty rowers rowing at full speed.

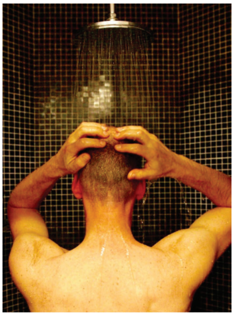


Figure 1.10 How much energy does taking a shower cost? [photo: Sandra Wensveen]

Knowing these basics, we can simply calculate the amount of energy required for showering.

It will not apply to most people, but for shower addicts, who spend an hour under warm water, will use the power of the boiler for 1 hour, costing 10 kilowatt-hours, or the equivalent of 1 litre of diesel. Think of taking a common milk carton filled with diesel to the shower.

- 1 hour: 10 kW * 1 h = 10 kWh = 1 l of diesel

A somewhat more modest shower user spending twenty minutes uses 3.3 kilowatt-hours.
You could say a beer bottle from a Belgian abbey filled with diesel.

- 20 minutes: 10 kW * 0.33 h = 3.3 kWh = 0.33 l of diesel

If you are a fast or environmentally conscious shower user, you will need a equivalent to a double whiskey glass of diesel.

- 5 minutes: 10 kW * 0.08 h = 0.8 kWh = 0.08 l of diesel

Energy used by buildings

Now let's return to our main topic: the building. How much energy does a typical household use for their building? The figures for the Netherlands are shown below.

- Heating, hot water and cooking: 1400 m^3 of natural gas[3] = 13.3 MWh_{therm}
- Lighting, ventilation and electric appliances: 3500 kWh of electricity = 3.5 MWh_{electr}

3 In the Netherlands, natural gas has a caloric value of 9.52 kWh/m^3.

Dutch households on average need 1400 cubic metres of gas for heating, hot water, and cooking. This is 13.7 megawatt-hours of thermal energy.
A further 3.5 megawatt-hours of electricity are needed for lighting, ventilation, pumps, and electric appliances. Converted and summed up, a Dutch household uses 16.8 MWh to run their home. We should however account for more …

The efficiency of power plants

Electricity is generated in power plants (figure 1.11), which usually burn fossil fuels for heat, which drives a generator that produces electricity. Not all of the fuel's energy content is converted to electricity: most of it is actually converted to waste heat. So, the kilowatt-hours of electricity you receive has cost more kilowatt-hours of fuel, which we call the primary energy.

Figure 1.11 Coal-fired power plant [photo: Andy van den Dobbelsteen]

In the Netherlands, around the time of writing, the average efficiency of power plants was 45%. Therefore, the 3.5 megawatt-hours has actually cost 7.8 megawatt-hours of primary energy. Together, the total amount of primary energy needed for the house is 21.5 megawatt-hours, or close to 10 megawatt-hours per person, accounting for 2.2 people per household on average.

If we want to become energy neutral, all this energy needs to be produced sustainably.
We will see further on if this is a lot. But first we need to understand the basics of the heat balance of a building, which will be discussed in the following section.

1.3 Heat Balance

BY ERIC VAN DEN HAM

What goes in must come out. That is basically the heat balance of any building, and you need some basic understanding of this when you want to reduce the energy demand of your building. The heat balance consists of heat gains on one side and heat losses on the other (figure 1.12).

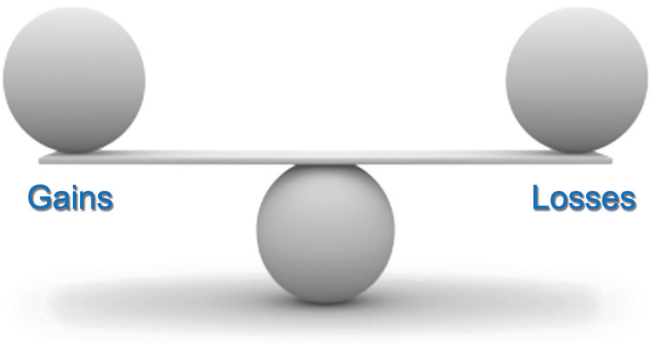


Figure 1.12 Heat balance [image: Eric van den Ham]

To better understand what a heat balance is, this section will use a typical Dutch terraced house. The dwelling of figure 1.13 was also the basis for the Prêt-à-Loger refurbishment project, which will be shown to you as an example throughout this book.

Figure 1.13 Terraced house in Honselersdijk, the Netherlands [photo: Eric van den Ham]

Improving the energy performance of buildings is an important step in the transition towards a sustainable economy. This book introduces you to zero-energy design. It demonstrates – in a clear, step-by-step approach – how to design new buildings as well as how to redesign existing structures to make them more energy efficient or even energy neutral. It's an integrated approach, which takes into account both passive measures (such as thermal insulation and sun shading) and active measures (such as heat pumps and photovoltaic panels).

Chapter 1 is an introductory chapter focussing on energy, power and heat balance. In Chapter 2 *Researching the local circumstances* the role of climate and the history and principles of bioclimatic design are discussed. The question of how to reduce energy demand is tackled in Chapter 3. Chapter 4 focusses on the use of residual energy. *Generating renewable energy,* Chapter 5, concentrates on solar power, biomass and environmental energy. All themes discussed in earlier chapters are integrated in the final Chapter 6.

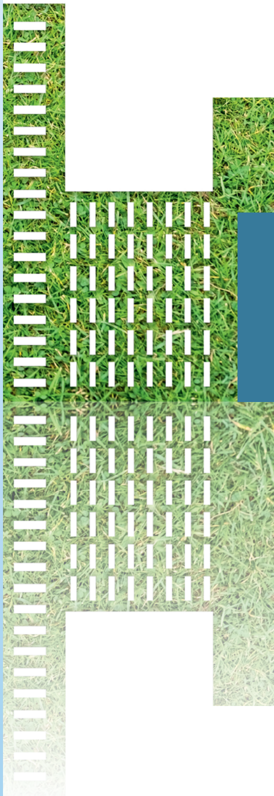
The theory in **Zero-Energy Design** is accompanied by full-colour images, illustrations, and practical cases of zero-energy design.

This book is accompanied by a website, **www.zero-energydesign.nl**, consisting of videos, assignments and the online book.

Zero-Energy Design is written for bachelor, master and post-master students of disciplines related to the built environment, such as architecture, architectural engineering, building engineering, building technology, building physics, construction, project development and building management.

Prof. Andy van den Dobbelsteen, PhD MSc is full professor of Climate Design & Sustainability and Sustainability Coordinator at TU Delft.

Other contributors are: Eric van den Ham, MSc, Tess Blom, MSc, Sabine Jansen, PhD MSc, Regina Bokel, PhD MSc, Siebe Broersma, MSc, Leo Gommans, PhD MSc and Michiel Fremouw, MSc.



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