Toward a Carbon Dioxide Neutral Industrial Park

A Case Study

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Summary

The industrial park of Herdersbrug (Brugge, Flanders, Belgium) comprises 92 small and medium-sized enterprises, a waste-to-energy incinerator, and a power plant (not included in the study) on its site. To study the carbon dioxide (CO_2) neutrality of the park, we made a park-wide inventory for 2007 of the CO_2 emissions due to energy consumption (electricity and fossil fuel) and waste incineration, as well as an inventory of the existing renewable electricity and heat generation. The definition of CO_2 neutrality in Flanders only considers CO_2 released as a consequence of consumption or generation of electricity, not the CO_2 emitted when fossil fuel is consumed for heat generation. To further decrease or avoid CO_2 emissions, we project and evaluate measures to increase renewable energy generation.

The 21 kilotons (kt) of CO_2 emitted due to *electricity* consumption are more than compensated by the 25 kt of CO_2 avoided by generation of renewable electricity. Herdersbrug Industrial Park is thus CO_2 neutral, according to the definition of the Flemish government. Only a small fraction (6.6%) of the CO_2 emitted as a consequence of fossil fuel consumption (*heat generation*) and *waste incineration* is compensated by existing and projected measures for renewable heat generation.

Of the *total* CO_2 emission (149 kt) due to energy consumption (electricity + heat generation) and waste incineration on the Herdersbrug Industrial Park in 2007, 70.5% is compensated by existing and projected renewable energy generated in the park. Forty-seven percent of the yearly avoided CO_2 corresponds to renewable energy generated from waste incineration and biomass fermentation.

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Introduction

The concept of sustainable development has become a guiding principle for governments, industries, and communities. For industrial activities, concepts such as pollution prevention (PP), cleaner production (CP), and industrial ecology (IE) promote innovative technologies and the shift from end-of-pipe techniques to pollution prevention at the source (Lowe and Evans 1995; Lambert and Boons 2002; Cohen-Rosenthal 2004; Mirata and Emtairah 2005).

In recent years, concepts from industrial ecology have been used in the planning and development of eco-industrial parks (EIPs), which are intended to increase business competitiveness, reduce waste and pollution, create jobs, and improve working conditions. An eco-industrial park can be defined as "a community of businesses cooperating with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat). This leads to economic gains, improves environmental quality, and enhances human resources for the business and local community" (PCSD 1997). Equilibrated development and growth—through maximized eco-efficiency of the park as a whole and through establishment of symbiotic relationships (exchange of material and energy streams) between companies—are the major focus of an eco-industrial park. Many EIPs are, however, still in their infancy, and their contribution to both economic development and environmental policy is complicated. In many locations, interfirm networking and collaboration through material exchange or energy cascading are not yet operational or are only in the early planning stage. Several sites in Europe apply industrial symbiosis, however. Examples are the Styria industrial park and Hartberg eco-park in Austria, ValuePark Schkopau in Germany, the BASF site Antwerp in Belgium, and Biopark Terneuzen in the Netherlands (Lambert and Boons 2002; Gibbs and Deutz 2003; Heeres et al. 2004; Mirata and Emtairah 2005; Vandecasteele et al. 2007; Deutz and Gibbs 2008; Van Dijck 2008; Liwarska-Bizukojc et al. 2009; van den Dobbelsteen et al. 2009; West-Vlaamse Intercommunale 2009).

In Flanders, Belgium, the principles of sustainable development have been incorporated in a ministerial act (Vlaamse Regering 2003) concerning cofinancing of business parks and office blocks in view of their sustainable design and management. Gradually, the elaboration of carbon neutrality in industrial environments gained ground, which led to the Flemish act on carbon dioxide (CO_2) neutrality as a prerequisite to subsidies for business park development (Vlaamse Regering 2007, 2009). Clustering industrial activities to reach CO_2 neutrality of an industrial park can be considered as a starting point and a stimulus for further intercompany collaboration; it can function as leverage to encourage companies toward economic, ecological, and social receptiveness, hence redirecting them toward corporate social responsibility. The objective of (concerted) carbon neutrality definitely adds to these principles (Holme and Watts 1999; Heeres et al. 2004; Van Eetvelde et al. 2007).

In this study, an inventory of the CO_2 emissions due to energy consumption (electricity and fossil fuel) and waste incineration, as well as an inventory of the existing renewable electricity and heat generation, has been made for Herdersbrug Industrial Park (Brugge, Flanders, Belgium) for 2007. To achieve CO_2 neutrality of Herdersbrug Industrial Park, we project and evaluate renewable electricity and heat generation as well as energy-saving measures. These are compared and ranked on the basis of their capacity for CO_2 reduction or compensation and their cost-effectiveness.

This study thus investigates the CO_2 neutrality of an industrial park in a broader sense than usual in Flanders. Introduction of renewable energy to an industrial park only makes sense after critical evaluation of the actual energy consumption and after implementation of energy-saving measures, such as relighting and insulation.

Carbon Dioxide Neutral Eco-Industrial Park

Emission of CO_2 by the combustion of fossil fuel is of great concern to scientists, technologists, and policy makers. On the international level, several countries approved the Kyoto Protocol, which aims to reduce greenhouse gas emissions for 2008–2012. Recently, the European Union (EU) set new guidelines for its member countries (20/20/20 objectives) intended to improve energy efficiency by 20%, introduce 20% renewable energy, and reduce greenhouse gas emission by 20% by 2020. As a consequence, EU governments have introduced measures and incentives to decrease fossil fuel consumption and to promote energy-saving methods and technologies (Hanley et al. 1997; Kunsch et al. 2004). An emission trading system has been imposed on the member states to stimulate energy-intensive sectors to reduce their CO_2 emissions. Unfortunately, no stringent engagements to reduce the emission of greenhouse gases were agreed on at the climate summit in Copenhagen (December 2009). Researchers stated that to limit global temperature increase to 2°C, developed countries must by 2020 reduce greenhouse gas emission by 25% to 40% compared to 1990 (Wikipedia 2009).

Nowadays, introduction of renewable energy and energy-saving measures is one of the main issues in EIPs in Flanders, Belgium. The Flemish government included the concept of CO_2 neutrality in the subsidy decree to design and manage new or to revitalize existing industrial parks (Vlaamse Regering 2007).

CO_2 neutrality is defined in Flanders as "CO_2 neutral electricity consumption by the companies in the park" or "compensation of CO_2 emissions due to electricity consumption" (Agentschap ondernemen 2009, 11). This can be achieved with renewable energy (produced in the park or purchased) or by compensation for CO_2 emissions with emission credits when nonrenewable electricity is used. In Flanders, only compensation of CO_2 emissions due to electricity consumption qualifies for subsidies to set up new or to revitalize existing industrial parks, not CO_2 emissions due to (nonelectrical) heating of buildings and to (nonelectrical) generation of process heat (Bourgeois 2008; Agentschap ondernemen 2009). In Flanders and in the Netherlands, these emissions represent about 40% of the total CO_2 emissions (Ministerie Economische Zaken Nederland 2008; Vlaamse Milieumaatschappij 2008). Heat can be generated from renewable sources, and residual heat from some high-temperature processes can have useful applications (Vandecasteele et al. 2007; Van Dijck 2008).

At the European level, no unequivocal vision on the generation and use of renewable heat exists, as is the case in Flanders. In 2007 the Therra Project was set up to formulate a definition for renewable heat and to develop a methodology to investigate potential renewable heat production in Europe (Therra Project 2007). The results of the Therra Project are a source of inspiration for directives on renewable heat in the EU. Some European countries have already introduced a number of measures to reduce fossil fuel consumption for heat production, the most important being design of heat charts; lists of supply and demand of hot and cold streams; screening of companies' heat consumption; subsidies for heat exchange in industry and agriculture; obligatory use of renewable energy for heat supply in new buildings; and financial support for heat projects, such as centralized industrial heating and construction of heat networks (Bundesministerium Deutschland 2008; Ministère de l' Ecologie France 2008; Ministerie van Economische Zaken Nederland 2008). Besides the allocation of subsidies to stimulate CO_2 neutrality of industrial parks, the Flemish government subsidizes "green electricity certificates" (per megawatt-hour [MWh] of electricity generated from renewable sources)[1] and "combined heat and power certificates" (per MWh energy saved with combined heat and power [CHP], compared to separate generation of electricity and heat recovery in a boiler).

Herdersbrug Industrial Park

Herdersbrug Industrial Park is situated along the Boudewijn channel (figure 1), which connects the seaport of Zeebrugge with the inner port of the city of Brugge (Belgium). The industrial park consists of 92 small and medium-sized companies with different activities, such as joinery, small trade, offices, storage and distribution, and production. Herdersbrug is thus a mixed industrial park. In mixed industrial parks, industrial activities of a diverse nature are concentrated in dedicated areas with little or no coupling of production processes (Lambert and Boons 2002).

Figure 1 Photograph of Herdersbrug Industrial Park (Brugge, Belgium). *Source:* Reproduced with permission of West-Vlaamse Intercommunale, Brugge, Belgium, 2011.

Besides the 92 companies, a combined-cycle gas turbine (CCGT) power plant (460 megawatt [MW] electrical),[2] fueled by natural gas, and a waste-to-energy plant (170 kilotons [kt] municipal solid waste/year)[3] are located on the park. Although the power plant emitted 840 kt of CO_2 in 2007, it was excluded from the study, because most of the customers of the power plant are situated outside Herdersbrug Industrial Park. The considered plant uses a highly efficient technology (steam and gas [STEG] power plant).

The municipal solid waste (MSW) incinerator is of the grate furnace type. There are 21 wind turbines at the Herdersbrug site, each of 600 kilowatts (kW). Two companies have installed solar panels on their roof.

The study of the CO_2 neutrality of Herdersbrug Industrial Park was initiated by the Provinciale Ontwikkelingsmaatschappij West-Vlaanderen (POM; Provincial Development Agency of the province) of West Flanders, where the industrial park is situated. Workshops and meetings to inform the companies on the park were and are still organized on a regular basis by the POM.

Inventory of Emitted and Avoided Carbon Dioxide

Inventories of CO_2 emissions due to energy consumption (electricity and fossil fuel) and waste incineration and of the existing renewable energy (electricity and heat) generation were made for Herdersbrug Industrial Park for 2007. Moreover, a number of measures for further reduction or compensation of CO_2 emissions were projected and evaluated. These were ranked on the basis of the avoided CO_2 emissions and cost-effectiveness (Van Praet and Windels 2009).

Data Acquisition

Electricity and natural gas consumption data were provided by the distribution grid operator Eandis. Fuel oil consumption data were collected by means of an inquiry. For 15 companies out of the 92 that use fuel oil, consumption data were not available. For these companies, fuel oil consumption was estimated with a tool developed by Hens (2008). The validity of the estimates was checked through comparison of real consumption data with estimates for six other companies with similar energy use and known consumption of fossil fuel; the difference was only 6%. Moreover, the estimated fuel oil consumption of the 15 companies accounted for only 2.8% of the total fuel oil consumption of the industrial park.

To calculate CO_2 emissions and avoided CO_2 emissions, we used emission factors. The Ministerial Decree for CO_2 Neutrality for Industrial Parks in Flanders proposes an emission factor of 0.6 kilograms carbon dioxide per kilowatt-hour (kg CO_2/kWh) for electricity consumption (Vlaamse Regering 2007). This corresponds to electricity production with fossil fuel but excludes nuclear power. This emission factor is preferred, as generation of renewable electricity will, in Belgium, not result in closure of a nuclear power plant (consequential approach; Finnveden et al. 2005). On the basis of the energy mix for electricity production in Belgium (FOD 2010) and the emission factors for power plants fueled by coal and natural gas (Donos et al. 2007), we obtained a similar value (0.62 kg CO_2/kWh). The emission factors for CO_2 of fossil fuel (0.264 kg CO_2/kWh) and natural gas (0.201 kg CO_2/kWh) were obtained from the Department of Environment of the Flemish Government (Velghe 2009). To calculate the avoided CO_2 emissions due to renewable electricity and heat generation, we used emission factors of, respectively, 0.6 kg CO_2/kWh and 0.201 kg CO_2/kWh (natural gas).

Table 1 Carbon dioxide (CO_2) emissions in the Herdersbrug Industrial Park in 2007 due to energy (electricity and fossil fuel) consumption and waste incineration (kilotons)

Energy consumption	*CO_2 emissions (kt)*
Electricity (92 companies)	21[a]
Fossil fuel (92 companies)	
Fuel oil	6[b]
Natural gas	24[c]
Waste incineration (nonbiogenic)	98
Total emissions	**149**

[a]Emission factor: 0.6 kilograms carbon dioxide per kilowatt-hour (kg CO_2/kWh).
[b]Emission factor: 0.264 kg CO_2/kWh.
[c]Emission factor: 0.201 kg CO_2/kWh.

Carbon Dioxide Emissions Due to Energy Consumption and Waste Incineration

The CO_2 emissions in 2007 due to energy (electricity and fossil fuel) consumption and waste incineration are given in table 1. CO_2 emissions corresponding to electricity consumption (34,300 MWh) of the 92 small and medium-sized companies amounted in 2007 to 21 kt; CO_2 emissions due to fuel oil (22,750 MWh) and natural gas (121,020 MWh) consumption amounted to 30 kt. The waste incinerator plant emitted 211 kt of CO_2 in 2007. From the composition of MSW in Flanders (Claes et al. 2007) and the biogenic carbon content of the different waste fractions, we calculated that 113 kt (53.5% of the 211 kt of emitted CO_2) was of biogenic origin (Astrup et al. 2009). Biogenic CO_2 is emitted during combustion of the organic fraction of MSW (kitchen and garden waste). As during growth crops absorb CO_2, which they release shortly thereafter during combustion, CO_2 balance can be considered. The biogenic CO_2 was subtracted from the total CO_2 emissions of the incineration plant. The nonbiogenic CO_2 emission of the waste incinerator was thus 98 kt. CO_2 emissions due to fossil fuel consumption and (nonbiogenic) waste incineration in Herdersbrug Industrial Park amounted in 2007 to 128 kt; together with the CO_2 emitted due to electricity consumption, a total CO_2 emission of 149 kt was obtained.

Renewable Energy Inventory

We made an inventory of the renewable electricity and heat generation in the park in 2007, together with the corresponding avoided CO_2 emissions (figures 2 and 3). There were 21 wind turbines in the park, each with a capacity of 600 kW, which corresponds to the yearly generation of 22,100 MWh of renewable electricity and the avoidance of 13 kt of CO_2 (for turbines on land, an efficiency of 20% is generally accepted).

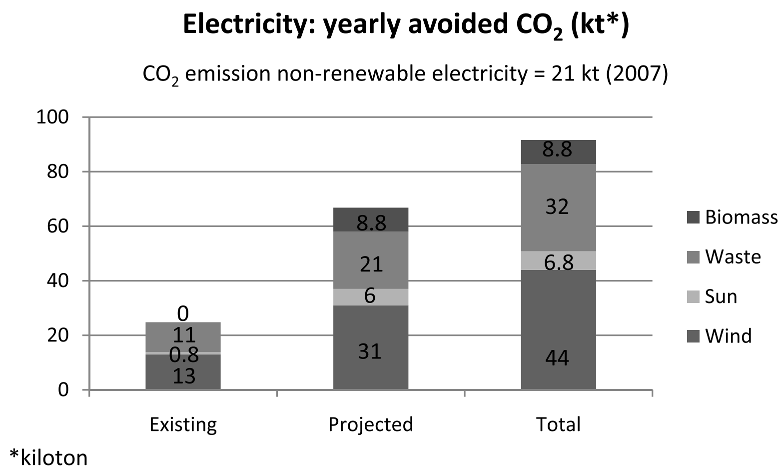

Figure 2 Avoided carbon dioxide (CO_2) emissions in Herdersbrug Industrial Park due to the generation of renewable electricity for existing (25 kilotons [kt]) and projected (67 kt) measures.

The roof of two companies (16,000 square meters [m^2])[4] was covered with photovoltaic panels, which generated yearly 1,300 MWh of renewable electricity (76.65 kWh/m^2, given a roof inclination of 30° and with shading taken into account), which avoids the emission of 0.8 kt of CO_2.

The boiler of the waste incinerator generates high-pressure steam, used to drive a 4-MW turbine to produce electricity (33,320 MWh yearly). After the turbine, low-pressure steam is passed through two heat exchangers to give water of 120°C and 8 bar, which is distributed through a heat network to ten customers. This hot water is used as process energy and for building heating (41,200 MWh). Because 53.5% of the waste is biogenic, 53.5% of the electricity and heat generated by waste incineration can be considered as renewable, which corresponds to 11 and 4.4 kt of avoided CO_2 emissions, respectively. Renewable energy in the Herdersbrug Industrial Park in 2007 corresponds thus to 29 kt of avoided CO_2, 25 kt from the generation of renewable electricity (wind energy, solar energy, and waste incineration) and 4.4 kt from renewable heat (waste incineration).

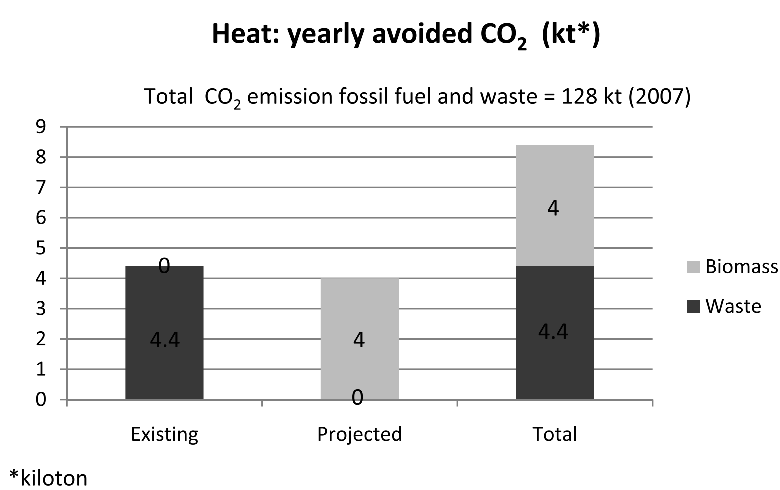

Figure 3 Avoided carbon dioxide (CO_2) emissions in Herdersbrug Industrial Park due to the generation of renewable heat for existing (4.4 kilotons [kt]) and projected (4 kt) measures.

Projected Measures and Avoided Carbon Dioxide Emissions

To further decrease or avoid CO_2 emissions, we projected and evaluated measures to increase the generation of renewable energy; their yearly avoided CO_2 emissions are given in figures 2 and 3.

Plans exist to replace the 21 turbines (each of 600 kW) with new ones with a capacity of 2 MW each. The planned wind turbines will, compared to the existing ones, yearly generate 51,500 MWh of extra renewable electricity, which corresponds to an avoided CO_2 emission of 31 kt (20% efficiency of the wind turbine). The extra renewable electricity generation due to covering the total roof surface of the buildings (from 16,000 m^2 to 147,000 m^2) with photovoltaic panels was estimated to generate an extra 10,000 MWh/year, which corresponds to 6 kt of avoided CO_2 emission. To increase its heat recovery efficiency, the waste incinerator plant started, in early 2010, to replace the 4-MW turbine with a 12-MW one, which corresponds to an extra yearly electricity generation of 66,600 MWh/year compared to the 4-MW turbine. In addition, 53.5% of the electricity (corresponding to the biogenic carbon content of the waste) can be considered as renewable energy and so avoids the emission of an extra 21 kt of CO_2. The feasibility of installing a biomass fermentation plant with a yearly capacity of 135 kt biomass was assessed (Colsen 2008). The building permit was applied for in the beginning of 2010. The biomass will consist of waste streams provided by companies on the site and by external companies. The produced biogas will be combusted in a CHP plant and thus used to generate electricity and heat. The heat will be transported through a heat network to a wax candle company, where it will be used as process energy; it will also be used for heating purposes in nearby companies. The biomass fermentation installation will generate 14,400 MWh/year of renewable electricity and 20,200 MWh/year of renewable heat, which corresponds to avoided emissions of 8.8 and 4 kt of CO_2, respectively. Projected renewable energy generation corresponds thus to 71 kt of avoided CO_2 emission: 67 kt from renewable electricity, and 4 kt from renewable heat generation.

Generation of renewable energy only makes sense after a critical evaluation of the actual energy consumption and the implementation of energy-saving measures. Therefore, we also considered the application of energy-saving measures such as relighting (e.g., dimming systems, daylight sensors, high-efficiency lighting, automatic approach detection) and building insulation. The quantification of the energy-saving measures (relighting and insulation) was based on the method developed by the British energy study BRECSU (BRECSU 2000). This study classifies industrial buildings (built in the 1980s) into four classes and compares their energy consumption before and after application of energy-saving measures. Most of the buildings in Herdersbrug are Class 2 buildings; these are characterized by office and production activities and have a restricted energy management, an inefficient energy use, and a total floor area between 500 and 4,000 m^2.

For Class 2, buildings electricity consumption is reduced by 42% (16 kWh/m^2) after the introduction of relighting measures, and fossil fuel consumption is reduced by 46% (69.5 kWh/m^2) after the insulation of buildings. Lighted floor surfaces (110×10^3 m^2) and roof and wall surfaces (270×10^3 m^2) for the different companies in Herdersbrug were estimated on the basis of information obtained from individual companies and from aerial photographs. Application of the BRECSU figures to the Herdersbrug site results in an annual CO_2 emission reduction of 1.1 kt (1,800 MWh) and 3.8 kt (18,800 MWh) for relighting and insulation, respectively. CO_2 emissions avoided by energy-saving measures and by existing and projected renewable energy (electricity and heat) are summarized in table 2.

Economic Study

We performed an economic study to estimate investment cost and payback time (table 3). The payback time is determined on the basis of the calculation of the net actual value:

$$\text{Net actual value} = \sum_{0}^{20} \textit{yearly discounted revenues} - \textit{investment costs}$$

with a discount factor of 4% and a yearly increase of energy prices of 3%; the net actual value is

Table 2 Avoided carbon dioxide (CO_2) emissions by existing and projected measures (electricity and heat)

Measure	*Existing*	*Projected*	*Total*
Wind turbines	13.0	31.0	44.0
Solar energy	0.8	6.0	6.8
Waste incineration	15.4	21	36.4
Biomass fermentation	-	12.8	12.8
Insulation of buildings	-	3.8	3.8
Relighting	-	1.1	1.1
Total	**29.2**	**75.7**	**104.9**

Note: Values are in kilotons.

calculated for a period of 20 years. The yearly discounted revenues take into account government allowances, savings by investment deductions, yearly extra income due to electricity generation, and green power certificates. Total investment costs and government allowances are considered in the year of execution of the project; the investment deduction is considered in the following year. Nonrecurrent expenses and initial investments are registered in the year of execution.

Is Herdersbrug Industrial Park Carbon Dioxide Neutral?

As appears from table 1, in 2007, the 92 companies in Herdersbrug Industrial Park consumed electricity corresponding to the emission of 21 kt of CO_2, whereas existing renewable electricity generation (wind, solar, waste incineration) in the park corresponded to 25 kt of avoided CO_2 (figure 2). This means that Herdersbrug Industrial Park was CO_2 neutral, according to the Flemish definition of CO_2 neutrality of industrial parks. The projected renewable electricity generation (wind, solar, waste incineration, biomass fermentation) corresponds to 67 kt of avoided CO_2 (figure 2). Existing and projected renewable electricity thus give 71 kt more avoided CO_2 yearly than required for CO_2 neutrality (Flemish definition).

When the CO_2 emitted due to fossil fuel combustion (heat generation) is also considered, the following CO_2 balance is obtained. The 92 companies of Herdersbrug Industrial Park emitted in 2007 30 kt of CO_2 due to fossil fuel combustion. The waste-to-energy plant emitted in 2007 98 kt nonbiogenic CO_2, which left a total of 128 kt of CO_2 to be compensated for the whole park (table 1). To date, only the waste-to-energy plant generates renewable heat, which corresponds to 4.4 kt of avoided CO_2 per year; 4 kt per year of avoided CO_2 is projected by biomass fermentation (figure 3). Existing and projected renewable heat generation thus compensate for only 6.6% of the 128 kt of CO_2 emitted by fossil fuel combustion and waste incineration.

Of the total CO_2 emission (149 kt/year) corresponding to the energy consumption and waste

Table 3 Estimated investment costs, payback times, avoided carbon dioxide (CO_2), and cost-effectiveness for the projected measures

Projected measure	*Investment costs (10^6 €)*	*Payback time*	*Total avoided CO_2[a] (%)*	*Cost-effectiveness*[b]
21 turbines 600 kW → 2 MW	50.4	6 years and 1 month	41	1.6
Solar energy roof surface 16,000 m^2 → 147,000 m^2	33	5 years and 7 months	8	5.5
Waste incineration 4 MW → 12 MW	27	6 years	28	1.3
Biomass fermentation	8.7	2 years and 3 months	17	0.7
Relighting	1.0	6 years and 6 months	1.5	0.9
Insulation	5.4	2 years and 9 months	5	1.4
Total	**125.5**			

Note: kW = kilowatts; MW = megawatts; m^2 = square meters.
[a]Projected measures: 76 kilotons (see table 2).
[b]Investment cost/yearly projected avoided CO_2 (€/kg).

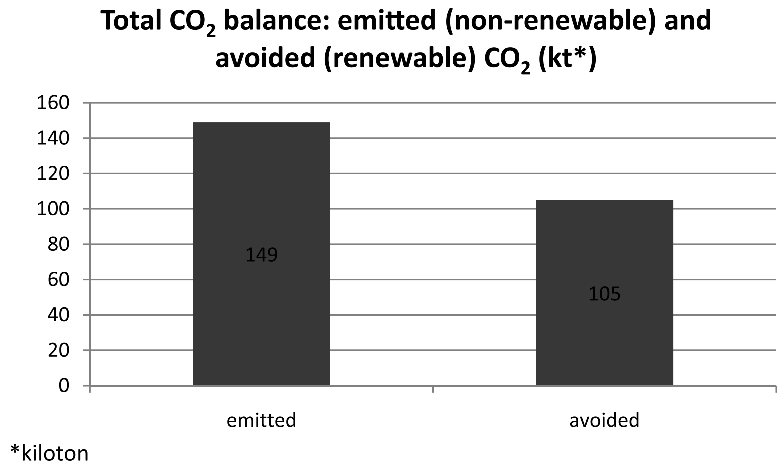

Figure 4 Carbon dioxide (CO_2) balance for Herdersbrug Industrial Park: emitted CO_2 by consumption of nonrenewable energy (electricity and heat) and waste combustion (149 kilotons [kt] in 2007) and yearly avoided CO_2 emissions by energy-saving measures and existing and projected renewable energy (105 kt).

incineration in Herdersbrug Industrial Park in 2007 (table 1), 100 kt (67%) can be compensated for by existing and projected renewable energy generated in the park. When we also include energy-saving measures, such as relighting (1.1 kt) and building insulation (3.8 kt), in the balance, the avoided CO_2 increases to 105 kt/year; this means that 70.5% of the emitted CO_2 is compensated (figure 4).

Investment costs and payback times for the projected methods are given in table 3. Total investment costs are estimated at 125.5×10^6 euro. The contributions to the total avoided projected CO_2 emissions for the different projected measures are given in percentages. The largest contributions are from wind energy, waste incineration, and biomass fermentation (41%, 28%, and 17%, respectively). To compare the cost-effectiveness of the projected measures, we calculated the ratio of investment cost to yearly avoided CO_2; the values are given in euros per kilogram CO_2 (table 3). There is not much difference among the methods, with the exception of solar energy, which is the least cost-effective (ratio of 5.5). The lowest ratios are obtained for renewable energy from biomass fermentation and for the application of relighting measures (0.7 and 0.9, respectively). Forty-seven percent of the yearly avoided CO_2 corresponds to renewable energy generated from waste treatment.

Discussion

Achieving CO_2 neutrality for an industrial park, according to the definition in Flanders, is feasible when only electricity consumption and renewable electricity generation are considered. When CO_2 emissions due to fossil fuel combustion and waste incineration (heat generation) are taken also into account, achieving CO_2 neutrality is more difficult. In Flanders, residual heat from important heat sources, such as waste incinerators and power plants, is seldom used. On the one hand, Flanders lacks heat distribution networks: For an efficient use of residual heat, the heat source needs to be close to the customers, and constant purchase of heat is required. On the other hand, equipment for the generation of renewable electricity, such as photovoltaic cells and wind turbines, is subsidized, and green electricity certificates (0.08–0.33 €/kWh; values for 2011) are obtained for the generated renewable electricity (VREG 2010). Residual heat is applied as process heat in industry, however. The BASF site in Antwerp (Belgium) connects endothermal and exothermal processes, so that only a small amount of additional energy is needed, which is produced in a power station to compensate for the energy deficit (Vandecasteele et al. 2007). Also at the Biopark Terneuzen (the Netherlands), residual heat is exchanged among companies, which improves the eco-efficiency of the park (Van Dijck 2008).

Listing supply and demand of hot and cold streams and screening heat consumption of companies, together with financial support for heat projects, such as centralized industrial heating and construction of heat networks, can create opportunities for renewable heat generation and use. Feasibility studies are necessary to prove the advantages of heat networks. Park managers but also the Flemish authorities should encourage companies to become part of intercompany networks. In old industrial parks, such as Herdersbrug Industrial Park, initiatives are indeed seldom considered. Fortunately, in new industrial parks, park managers play an important role: They have to watch over the rules and agreements for the setting up of new parks—CO_2 neutrality being one of them—and select companies according to these rules.

Conclusion

It can be concluded that the Herdersbrug Industrial Park is CO_2 neutral according to the definition of CO_2 neutrality of industrial parks in Flanders. Existing and projected renewable electricity generation even give 71 kt more avoided CO_2 yearly than required for CO_2 neutrality. From the CO_2 emitted due to the consumption of fossil fuel and waste incineration, only 6.6% is compensated for by existing and projected measures. From the total CO_2 emission (149 kt) corresponding to the energy consumption of Herdersbrug Industrial Park in 2007, 70.5% can be neutralized by energy-saving measures, waste incineration, and existing and projected renewable energy generated in the park. Waste treatment can play an important role in achieving CO_2 neutrality of an industrial park, even waste incineration, which is not considered as renewable in the strict sense. Combustion of the biogenic fraction of the waste generates renewable energy, and the combustion of the nonbiogenic carbon is also beneficial, because it avoids the consumption of an equivalent amount of fossil fuel.

Industrial parks can achieve CO_2 neutrality by purchasing renewable energy or generating renewable energy themselves. A sustainable energy strategy is only possible if it is outlined by the park manager together with the tenants of the park and is supported by policy makers. Attention should be given so that the choice of renewable energy measures depends on more than the attitude of the companies toward the mix of subsidies and ruling energy prices.

Carbon neutrality of industrial parks can be considered as a starting point and a stimulus for further intercompany collaboration. The creation of an energy conscience is necessary for a cost-effective sustainable energy strategy that is part of the energy policy of companies and industrial parks (Maes et al. 2011; van den Dobbelsteen et al. 2009). In the future, reuse of residual heat and generation of renewable heat should be stressed in the renewable energy strategy of Flanders; this could be initiated, for example, by a broader definition of the CO_2 neutrality of industrial parks. Striving for renewable energy is the final target of a sustainable energy strategy, but in the first place, reduction of energy consumption must be focused on thorough process optimization and energy efficiency!

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Notes

1. One megawatt-hour (MWh) $\approx 3.6 \times 10^9$ joules (J, SI) $\approx 3.412 \times 10^6$ British Thermal Units (BTU).
2. One megawatt (MW) = 10^6 watts (W, SI) = 1 megajoule/second (MJ/s) $\approx 56.91 \times 10^3$ British Thermal Units (BTU)/minute.

3. One kilotonne (kt) = 10^3 tonnes (t) = 10^3 megagrams (Mg, SI) ≈ 1.102 × 10^3 short tons.
4. One square meter (m^2, SI) ≈ 10.76 square feet (ft^2).

References

Agentschap Ondernemen [Enterprise Agency]. 2009. Handleiding CO_2-neutraliteit. [Compendium CO_2 neutrality.] www.agentschapondernemen.be. Accessed September 2009.

Astrup, T., J. Møller, and T. Fuergaard. 2009. Incineration and co-combustion of waste accounting of greenhouse gases and global warming contributions. *Waste Management & Research* 27(8): 789–799.

Bourgeois, C. 2008. De concrete stappen naar CO_2-neutraliteit. [Steps to CO_2 neutrality.] In *Milieudirect*. Belgium: Kluwer.

BRECSU (Building Research Energy Conservation Support Unit). 2000. *Energy use in offices*. Crown, UK: Energy Technology Support Unit (ETSU).

Bundesministerium für Umwelt, Naturschutz und Reactorsicherheit Deutschland [Federal Ministry for the Environment, Nature Conservation and Reactor Safety]. 2008. The Renewable Energy Heat Act. www.umwelt-und-energie.de/files/pdfs/allgemein/application/pdf/ee_waermegesetz_fragen_en.pdf. Accessed February 2009.

Claes, K., A. Van Der Linden, K. Briffaerts, L. Putseus, L. Umans, M. De Groof, D. Wille, A. Vandeputte, A. D'Haese, V. Dons, and E. Vander Putten. 2007. Milieurapport Vlaanderen MIRA, achtergronddocument, Thema Beheer van Afvalstoffen. [Environmental report of Flanders MIRA, background document: Theme waste management]. www.vmm.be. Accessed December 2008.

Cohen-Rosenthal, E. 2004. Making sense out of industrial ecology: A framework for analysis and action. *Journal of Cleaner Production* 12: 1111–1123.

Colsen, Adviesbureau voor milieutechniek [Consulting Office for Environmental Technology]. 2008. *Haalbaarheidsstudie naar Biogasvergisting in de Haven van Zeebrugge*. [Feasability study for biomass fermentation in the port of Zeebrugge.] Hulst, the Netherlands: Colsen, Adviesbureau voor milieutechniek.

Deutz, P. and D. Gibbs. 2008. Industrial ecology and regional development as cluster policy. *Regional Studies* 42(10): 1313–1328.

Donos, R., C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Röder, M. Emmenegger, R. Frischknecht, N. Jungbluth, and M. Tuschmid. 2007. *Life cycle inventories of energy systems: Results for current systems in Switzerland and other UCTE countries*. Ecoinvent report No. 5. Villigen, Switzerland: Paul Scherrer Institut.

Finnveden, G., J. Johansson, P. Lind, and A. Moberg. 2005. Life cycle assessment of energy from solid waste—Part 1: General methodology and results. *Journal of Cleaner Production* 13: 213–229.

FOD (Federale Overheidsdienst) Economie [Federal Civil Service for the Economy]. 2010. *KMO (Kleine en Middelgrote Ondernemingen), Middenstand en Energie: De Energiemarkt in 2007*. [Small and middle-sized companies and energy: The energy market in 2007.] http://economie.fgov.be. Accessed January 2010.

Gibbs, D. and P. Deutz. 2004. Implementing industrial ecology? Planning for eco-industrial parks in the USA. *Geoforum* 36: 452–464.

Hanley, N., J. F. Shogren, and B. White, eds. 1997. *Environmental economics in theory and practice*. Houndsmill, UK: Macmillan.

Heeres, R., W. Vermeulen, and F. de Walle. 2004. Eco-industrial initiatives in the USA and the Netherlands: First lessons. *Journal of Cleaner Production* 12: 985–997.

Hens, H. 2008. *Industriële gebouwen: Energieverbruik*. [Industrial buildings: Energy consumption.] Leuven, Belgium: Departement Burgerlijke Bouwkunde KU Leuven.

Holme, R. and P. Watts. 1999. *Meeting changing expectations: Corporate social responsibility*. WBCSD Publications ISBN No. 2-94-0240-03-5. Geneva, Switzerland: World Business Council for Sustainable Development.

Kunsch, P., J. Springael, and J. Brans. 2004. The zero-emission certificates: A novel CO_2-pollution reduction instrument applied to the electricity market. *European Journal of Operational Research* 153: 386–399.

Lambert, A. and F. Boons. 2002. Eco-industrial parks: Stimulating sustainable development in mixed industrial parks. *Technovation*. 22: 471–484.

Liwarska-Bizukojc, E., M. Bizukojc, A. Marcinkowski, and A. Doniec. 2009. The conceptual model of an eco-industrial park based upon ecological relationships. *Journal of Cleaner Production* 17: 732–741.

Lowe, E. and L. Evans. 1995. Industrial ecology and industrial ecosystems. *Journal of Cleaner Production* 3: 47–53.

Maes, T., G. Van Eetvelde, E. De Ras, C. Block, A. Pisman, B. Verhofstede, F. Vandendriessche, and L. Vandevelde. 2011. Energy management on mixed industry parks in Flanders. *Renewable and Sustainable Energy Reviews*15: 1988–2005.

Ministère de l'Ecologie, de l'Energie, du Development Durable et de l'Aménagement du Territoire [Ministry of the Environment, Energy, Sustainable Development and Renovation of the Territory, France]. 2008. *Grenelle environnement: Reussir la transition energétique*. [How to succeed to the energy transition.] www.developpement-durable.gouv.fr. Accessed March 2009.

Ministerie van Economische Zaken Nederland [Ministry of Economic Affairs of the Netherlands]. 2008. *Warmte op Stoom: Werkprogramma voor de Verduurzaming van Warmte- en Koudevoorziening*. [Heat from steam: Program for the preservation of heat and cold supply.] www.ez.nl. Accessed March 2009.

Mirata, M. and T. Emtairah. 2005. Industrial symbiosis networks and the contribution to environmental innovation: The case of the Landskona industrial symbiosis program. *Journal of Cleaner Production* 13: 993–1002.

PCSD (U.S. President's Council on Sustainable Development). 1997. Proceedings for the Eco-industrial Park Workshop, 17–18 October 1996. http://clinton2.nara.gov/PCSD/Publications/Eco_Workshop.html. Accessed June 2011.

Therra Project. 2007. Proposal for the definition and calculation principle for renewable energy. http://circa.europa.eu/Public/irc/dsis/chpwg/library?l=/statistics_30112007/therra-calculation/_EN_1.0_&a=d. Accessed May 2009.

Vandecasteele, C., J. Van Caneghem, and C. Block. 2007. Cleaner production in the Flemish chemical industry. *Clean Technologies and Environmental Policy* 9: 37–42.

Van den Dobbelsteen, A., N. Tillie, D. Doepel, M. Joubert, and W. de Jager. 2009. Towards CO_2 neutral urban planning: Presenting the Rotterdam Energy Approach and Planning (REAP), 45th ISOCARP Congress 2009. www.isocarp.net/Data/case_studies/1488.pdf. Accessed March 2009.

Van Dijck, B. 2008. *Restromen in the Gentse Kanaalzone*. [Rest streams in the Canal Zone of Ghent.] Coordination Cell for Sustainable Development of the Flemish Government. www.dbt.ugent.be/pdf/reststromen_eindpublicatie.pdf. Accessed October 2008.

Van Eetvelde, G., K. Deridder, S. Segers, T. Maes, and M. Crivits. 2007. Sustainability scanning of eco-industrial parks. Paper presented at the 11th European Roundtable on Sustainable consumption and Production (ERSCP), 20 – 22 June, Basel, Switzerland.

Van Praet, B. and T. Windels. 2009. Naar een CO_2-neutraal Industrieel Park. [Toward a CO_2 neutral industrial park.] Master's thesis, Catholic University of Leuven, Leuven, Belgium.

Velghe, T., 2009. Personal communication with T. Velghe, Departement Leefmilieu, Natuur en Energie van de Vlaamse Overheid (LNE) [Department of Environment, nature and energy of the Flemish Government]. Flanders, Belgium, May 2009.

Vlaamse Milieumaatschappij (VMM) [Flemish Environmental Agency]. 2008. *Emissie Inventaris Lucht, Lozingen in de lucht 1990 – 2007*. [Emission inventory of air pollution, emissions 1990–2007]. Depotnummer D/2008/6871/044. Vlaamse Milieumaatschappij, Mechelen, Belgium.

Vlaamse Regering [Flemish Government] 2003. *Besluit van de Vlaamse Regering van 5 september 2003 houdende subsidiëring van Bedrijventerreinen, Wetenschapsparken en Bedrijfsgebouwen*. [Decree of the Flemish Government of the 5th of September 2003 concerning subsidizing industrial parks, science parks, and company buildings.] Belgian Bulletin of Acts, Orders and Decrees 05/02/2004. Brussels, Belgium.

Vlaamse Regering [Flemish Government]. 2007. *Ministerieel besluit van 1 oktober 2007 houdende de uitwerking van de CO_2-Neutraliteit op Bedrijventerreinen*. [Ministerial decree of 1st of October concerning the elaboration of the CO_2 neutrality of industrial parks.] Belgian Bulletin of Acts, Orders and Decrees 15/10/2007. Brussels, Belgium.

Vlaamse Regering [Flemish Government]. 2009. *Ministerieel Besluit van 5 juni 2009 tot Wijziging van Artikelen 5, 6, 8, 10 en 11 van het Ministerieel Besluit van 1 oktober 2007 houdende de uitwerking van de CO_2-Neutraliteit op de Bedrijventerreinen*. [Ministerial decree of 5th of June for the amendement of the articles 5, 6, 8, 10 and 11 of the ministerial decree of the 1st of October 2007 concerning the elaboration of the CO_2 neutrality of industrial parks.] Belgian Bulletin of Acts, Orders and Decrees 08/07/2009. Brussels, Belgium.

VREG. 2010. www.vreg.be. Accessed August 2010.

West-Vlaamse Intercommunale. 2009. *Deelplan CO_2-Neutraliteit, Site Kazerne Lissewege, Belgium*. [Subplan CO_2-neutrality, Site barracks Lissewege, Belgium]. Belgium: West-Vlaamse Intercommunale.

Wikipedia. 2009. United Nations Climate Change Conference. http://en.wikipedia.org/wiki/2009_United_Nations_Climate_Change_Conference. Accessed 20 May 2010.

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