Report on Energy in the Urban Water Cycle

E2STORMED PROJECT
Improvement of energy efficiency in the water cycle by the use of innovative storm water management in smart Mediterranean cities
www.e2stormed.eu
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1. STORMWATER MANAGEMENT IN THE URBAN WATER CYCLE

1.1. ENERGY CONSUMPTION IN THE URBAN WATER CYCLE

Urban Water use cycle refers to the overall process of collecting, developing, conveying, treating, and delivering water to end users; using the water; and collecting, treating, and disposing of wastewater. It begins with the water collection or extraction from a source. Then, it is transported to water treatment facilities and distributed to end users. Next it is collected and treated in a wastewater plant, prior to be discharged back to the environment, where it becomes a source for someone else.

Energy intensity is defined as the amount of energy consumed per unit of water to perform water management-related actions such as desalting, pumping, pressurizing, groundwater extraction, conveyance, and treatment - for example, the number of kilowatt-hours consumed per cubic meter (kWh/m$^3$) of water. But, this concept is also applied to water supplies or infrastructure construction and operation.

In this report, energy consumption of the implementation of different urban drainage systems has been studied. The analysis comprises different aspects of their integration into the urban water cycle, such as its construction and operation and management, as well as their impact over the water distribution, water treatment and wastewater treatment stages.

Next, a calculation method is included for each energy analysis in order to provide a better understanding of the different considerations made in the study.

Figure 1.1. Stages of the water life cycle through the municipal sector (Wilkinson, 2000) and (Lienhard, 2010)
1.2. Relation between CO₂ Emissions and Energy

Energy may have different forms depending on the source or energy vector used (any type of fuel, electricity or any other energy vector, such as hydrogen). For the purpose of this study, it has been differentiated between electricity and fuel consumption.

Use of Electricity

Energy needs are different for each country, as well as energy uses and sources. The term ‘Energy mix’ refers to the distribution, within a given geographical area, of the consumption of various energy sources (crude oil, natural gas, coal, nuclear energy, and renewable energy) when consuming electricity.

Thus, CO₂ Emissions of using electricity as an energy vector depends on the energy mix of each country, which is calculated according to their energy resources composition and depends on the following factors:

- The availability of resources or the possibility of importing them
- The extent and nature of energy needs to be met
- The economic, social, environmental, and geopolitical context
- The political choices resulting from the above

Next, the table represents the grams of CO₂ emissions per kWh produced by the electricity generation system of each country, depending on the energy sources available at each region.

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TABLE 1. CO₂ Emissions (g CO₂ per kWh) per country due to electricity consumption (IEA, 2012)

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Emission Factors depend on the country, in case of electricity (generation mix), and on the type of fuel (no country dependence). Additional indicators for other countries may be found at the Emission Factors from Cross-Sector Tools (GHG Protocol, 2012).

**Use of Other Fuels**

CO₂ emissions due to the consumption of fuel don’t depend of the specifics of the country, but the fuel properties (such as the heating value). In the next table it is provided a referenced relation of the different emission factors per type of fuel:

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<th>Mass basis</th>
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<th>Gas basis</th>
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<td>0.26</td>
<td></td>
<td></td>
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<tr>
<td>White Spirit/SBP</td>
<td>40.2</td>
<td>73300</td>
<td>2947</td>
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<tr>
<td>Other petroleum products</td>
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<td>73300</td>
<td>2947</td>
<td>0.26</td>
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<td></td>
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<td>Coal products</td>
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<td>Anthracite</td>
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<td>2624.61</td>
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<tr>
<td>Coking coal</td>
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<td>94600</td>
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<tr>
<td>Other bituminous coal</td>
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<td>94600</td>
<td>2440.68</td>
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<tr>
<td>Sub bituminous coal</td>
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<td>1816.29</td>
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<tr>
<td>Lignite</td>
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<td>101000</td>
<td>1201.9</td>
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<td>Oil shale and tar sands</td>
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<td>107000</td>
<td>952.3</td>
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<td></td>
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<tr>
<td>Brown coal briquettes</td>
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<td>97500</td>
<td>2018.25</td>
<td>0.35</td>
<td></td>
<td></td>
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<tr>
<td>Patent fuel</td>
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<td>97500</td>
<td>2018.25</td>
<td>0.35</td>
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<td></td>
</tr>
<tr>
<td>Coke oven coke</td>
<td>28.2</td>
<td>107000</td>
<td>3017.4</td>
<td>0.39</td>
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</tr>
<tr>
<td>Lignite coke</td>
<td>28.2</td>
<td>107000</td>
<td>3017.4</td>
<td>0.39</td>
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<tr>
<td>Gas coke</td>
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<td>107000</td>
<td>3017.4</td>
<td>0.39</td>
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<tr>
<td>Coal tar</td>
<td>28</td>
<td>80700</td>
<td>2259.6</td>
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<td>Gas works gas</td>
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<td>44400</td>
<td>1718.28</td>
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<tr>
<td>Coke oven gas</td>
<td>38.7</td>
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<tr>
<td>Natural gas</td>
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<tr>
<td>Natural gas</td>
<td>48</td>
<td>56100</td>
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<tr>
<td>Other wastes</td>
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<tr>
<td>Municipal waste (Non biomass fraction)</td>
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<td>0.33</td>
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<td>Industrial wastes</td>
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<td>143000</td>
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<tr>
<td>Waste oils</td>
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<td>73300</td>
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<td>Biomass</td>
<td>CO₂ Emissions (g CO₂ per kWh)</td>
<td>Energy Content (kWh)</td>
<td>Emission Factor (g CO₂ per kWh)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------------</td>
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<tr>
<td>Wood or Wood waste</td>
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<td>112000</td>
<td>1747.2</td>
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<td></td>
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<td>Sulphite lyes (Black liquor)</td>
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<td>100000</td>
<td>1160</td>
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<td></td>
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<td>Charcoal</td>
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<td>112000</td>
<td>3304</td>
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<td>Biogasoline</td>
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<td>70800</td>
<td>1911.6</td>
<td>0.25</td>
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<td>Biodiesels</td>
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<td>1911.6</td>
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<td>Other liquid biofuels</td>
<td>27.4</td>
<td>79600</td>
<td>2181.04</td>
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<tr>
<td>Landfill gas</td>
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<td>54600</td>
<td>2751.84</td>
<td>2.47</td>
<td>0.20</td>
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</tr>
<tr>
<td>Sludge gas</td>
<td>50.4</td>
<td>54600</td>
<td>2751.84</td>
<td>0.20</td>
<td></td>
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<tr>
<td>Other biogas</td>
<td>50.4</td>
<td>54600</td>
<td>2751.84</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal wastes (Biomass fraction)</td>
<td>11.6</td>
<td>100000</td>
<td>1160</td>
<td>0.36</td>
<td></td>
<td></td>
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<tr>
<td>Peat</td>
<td>9.76</td>
<td>106000</td>
<td>1034.56</td>
<td>0.38</td>
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</tbody>
</table>

*Table 1.2. CO₂ Emissions (g CO₂ per kWh) per (g CO₂ per kWh) per type of fuel (Greenhouse Gas Protocol, 2012)*
2. **INFRASTRUCTURE CONSTRUCTION AND MAINTENANCE**

Infrastructure, construction, operation and maintenance of drainage systems involve energy consumption, and must be considered in order to analyze energy efficiency of the Urban Water Cycle. Furthermore, an environmental impact is linked to energy consumption and it is usually estimated by calculating CO₂ emissions associated, as this expresses the potential of global warming. Thus, both energy consumption and environmental impact need to be evaluated.

The construction of urban water infrastructure systems involves a large consumption of different resources (water, energy, etc). Consequently, energy demand for conventional and sustainable urban drainage systems requires energy mainly in the form of electricity and fuel. Some examples include: energy to modulate the topography, energy for the production of building materials, etc.

Most elements of sustainable urban drainage systems do not require energy input for operation, since the use of gravity is very common. In addition, construction and maintenance of such systems usually involves an increased focus on site management, encouraging resource efficiency and CO₂ emissions avoided due to:

- reducing construction, demolition and excavation waste to landfill
- reducing carbon emissions from construction processes and associated transport
- ensuring products used in construction are responsibly sourced
- reducing water usage during the construction process
- carrying out biodiversity surveys and following up with necessary actions

Energy demand in drainage systems construction is calculated taking into consideration the energy consumed (electricity and fuel) and the materials used per m, m² or m³, which is also associated to an energy used and CO₂ emission factor per material manufacturing. There exist several CO₂ emission national databases that provide these parameters such as *Construmática* in Spain (ITeC, 2013) or Environmental Agency in UK (Environment Agency, 2007), which are used as reference; however, it is convenient to consider country-specific coefficients to guarantee that the specific characteristic of the industry at each country are considered.
**Table 2.1. “Construmática” example of greenroof materials**

<table>
<thead>
<tr>
<th>Category</th>
<th>Specific material</th>
<th>Own data: density of material</th>
<th>Own data: CO2e/t material</th>
<th>Base data: density of material</th>
<th>Base data: CO2e/t material</th>
<th>Boundaries</th>
<th>Source ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarried aggregate</td>
<td>Quarried aggregate</td>
<td>1.9 tonnes/m³</td>
<td>0.3 tonnes/m³</td>
<td>Own data: density of material</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
<td>3</td>
</tr>
<tr>
<td>Stone</td>
<td>Vitrified clay pipe DN 100 &amp; DN 150</td>
<td>2.4 tonnes/m³</td>
<td>0.3 tonnes/m³</td>
<td>Own data: density of material</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<tr>
<td>Shale</td>
<td>Sand</td>
<td>2.4 tonnes/m³</td>
<td>0.005 tonnes/m³</td>
<td>Own data: density of material</td>
<td>Own data: CO2e/t material</td>
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<tr>
<td>Sandstone</td>
<td>Slate</td>
<td>1.6 tonnes/m³</td>
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<td>Own data: density of material</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
<td>1</td>
</tr>
<tr>
<td>Limestone</td>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>0.043 tonnes/m³</td>
<td>Own data: density of material</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<tr>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
<td>1</td>
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<tr>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
<td>1</td>
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<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<tr>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
<td>1</td>
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<tr>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<tr>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
<td>Own data: CO2e/t material</td>
<td>cradle to gate</td>
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<tr>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
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<td>cradle to gate</td>
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<tr>
<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
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<td>Clay: general (simple baked products)</td>
<td>1.8 tonnes/m³</td>
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<td>Clay: general (simple baked products)</td>
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<td>Clay: general (simple baked products)</td>
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<td>Clay: general (simple baked products)</td>
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<td>cradle to gate</td>
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<td>cradle to gate</td>
<td>1</td>
<td></td>
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</tr>
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</table>

**Table 2.2. Environment Agency Carbon Calculator for Materials**
2.1. CONSTRUCTION AND MAINTENANCE

This section includes the description of the methodology used for calculating the energy consumption and emissions associated to the construction and maintenance of drainage systems (conventional and sustainable). Construction of drainage systems consists of several activities, which are different depending on the function and the complexity of the system. The methodology used in this report organizes the construction activities in work units in order to disaggregate energy consumption and its respectively associated emissions. Therefore, the total energy consumed (and emissions) in the construction of a drainage system corresponds to the sum of energy and emissions associated to each constructive activities. Energy consumption and CO₂ emissions related to the construction of a drainage system are expressed in kWh and kg CO₂e per size unit, respectively. Size Units are m, m² or m³ depending on the drainage system. Total values for a system can be easily obtained by adding calculations for its work units.

Regarding Maintenance, it is organized in two categories:

- **Periodic maintenance (every several years)**, mainly includes maintenance tasks that imply the reposition or replacement of materials and other activities carried out every several years. It includes both scheduled maintenance and reactive maintenance, i.e. when repair or refurbishment is necessary. It estimates the energy consumption and associated emissions of refurbishing the drainage system per damage or maintenance indication (material wear and replacement). Trips are not included in this indicators, transport is evaluated separately in the Annual Maintenance.

- **Annual maintenance (several times during the year)**, which estimates the energy consumed and emissions associated to transport. In this case it is evaluated the number of trips per year necessary for adequately maintaining the drainage system. These visits include necessary trips for performing maintenance activities (e.g. grass cutting) and regular trips for drainage system inspection. Generally, regular trips for inspection are also used to perform any required maintenance task.

Next, it is provided in Table 2.3 the results of the methodology applied to different drainage systems (conventional and sustainable) to estimate the energy consumption and emissions per size unit. Construction indicators correspond to the sum of the energy consumed in each constructive activity (e.g. excavation), while Periodic Maintenance values relate to refurbishing (e.g. Remove, dispose and replace top gravel layer). It does not include the energy consumed and emissions associated to the trips. Fuel consumption and associated emissions due to transport are estimated separately in the Annual Maintenance.
Report on Energy in the Urban Water Cycle

Table 2.3. Energy Consumption and CO₂ Emissions Indicators for Drainage System Construction and Maintenance.

Source: Prepared by the authors

Annual Maintenance (maintenance during the year) involves inspection & monitoring activities and frequent conservation tasks (i.e. grass mowing in swales). The methodology includes the assessment of the energy and CO₂ emissions due to transport, since it is the most significant. Energy and emissions associated to the conservation tasks (in case of any) are included in the scope of this approach.

Finally it has to be noted that Operation activities have not been considered in this methodology (Ex. pumping consumption in drainage systems operation. Nevertheless, you may find this data in the energy (electrical or fuel) bills or at the facility energy data meters (if available). As general indication, energy consumption associated to operation may be calculated as the sum of each equipment average power multiplied by the number of annual working hours. Consequently, emissions should be estimated as the energy consumed times the emission factor of the fuel or electricity (specific of the country).
2.2. CONSTRUCTION ENERGY CONSUMPTION CALCULATION METHOD

In order to obtain previous values, as shown in Table 2.3, a calculation method has been developed to estimate energy consumed in the construction of various drainage systems.

The first step in the evaluation is to compile the following information and data for the drainage system studied:

- **Technical description**: identify construction activities and define work units. Work units should be defined by a civil engineer or a drainage system expert. Sometimes construction activities coincide with work units. For instance, excavation is an activity which can be used as a work unit defined as m\(^3\) of excavation with specific characteristics. In other cases construction activities and work units don’t match and the last ones are individual components, such as a pipe, a valve or a sand layer. For instance, filling is an activity where work units could be m\(^3\) of gravel plus m\(^2\) of geotextile, both with specific characteristics.

- **Dimensions**: in order to quantify work units, it is necessary to estimate the required amount of each work unit per size unit. This is a complex task and is not standardized; this must be calculated by a civil engineer. For instance: 0.7 m\(^3\) of excavation per m\(^2\) of swale.

Once work units have been defined and quantified, energy consumption and CO\(_2\) emissions involved in the construction of a drainage system may be calculated, by calculating the difference between machinery and materials. Machinery refers to the consumption of energy and CO\(_2\) emissions associated to the equipment used (electricity or fuel); while materials relate to the energy and CO\(_2\) emissions related to the manufacturing processes of such materials.

- **Machinery**

  Two forms of energy have been identified:

  - Electricity: electrical machinery used in drainage system construction.
  - Fuel: machinery fuel used in drainage system construction.

- **Materials**

  Two forms of energy have been identified:

  - Electricity: electric energy used in material production processes.
  - Fuel: energy from fuels (Coal, LPG, Oil, Natural Gas and Others) used in material production processes.

Following sections include a description of the mathematical expressions for calculating energy consumption and CO\(_2\) emissions of each drainage system’s work unit. As mentioned above,
calculations are structured in two categories: machinery and material considering electricity and fuel needs.

### 2.2.1. Machinery

#### Electricity for a work unit

Energy consumption for a work unit is calculated by the following expression:

\[
EC_{\text{elec.mach.},i} \left( \frac{kWh}{\text{work unit}} \right) = P_{\text{elec.mach.}}(kW) \cdot OT_{\text{elec.mach.}} \left( \frac{h}{\text{work unit}} \right)
\]

*Equation 2.1*

Where:

- \(EC_{\text{elec.mach.},i}\) = *Energy consumption by electric machinery per work unit* (\(\frac{kWh}{\text{work unit}}\))
- \(i = \text{work unit}\)
- \(P_{\text{elec.mach.}}\) = *Electric machinery average power*(kW)
- \(OT_{\text{elec.mach.}}\) = *Operation time of electrical machinery* (\(\frac{h}{\text{work unit}}\))

Then, emissions for the same work unit can be calculated as follows:

\[
E_{\text{elec.mach.},i} \left( \frac{kg CO_2e}{\text{work unit}} \right) = EC_{\text{elec.mach.}} \left( \frac{kWh}{\text{work unit}} \right) \cdot EF_{\text{elec.count.}} \left( \frac{kg CO_2e}{kWh} \right)
\]

*Equation 2.2*

Where:

- \(E_{\text{elec.mach.},i}\) = *Emissions by electric machinery per work unit* (\(\frac{kg CO_2e}{\text{work unit}}\))
- \(EF_{\text{elec.count.}}\) = *Emission factor for electricity production of a country or region* (\(\frac{kg CO_2e}{kWh}\))

As an example, emission factor of EU-27 of electricity for 2010 is 0.347 kgCO₂/kWh.

#### Fuel for a work unit
Energy consumption for a work unit is calculated by the following expression:

\[
EC_{\text{fuel mach.}i} \left( \frac{kWh}{\text{work unit}} \right) = \sum_k \left[ P_{\text{fuel mach.}k} \left( kW \right) \cdot OT_{\text{fuel mach.}k} \left( \frac{h}{\text{work unit}} \right) \right]
\]  

Equation 2.3

Where:

\( EC_{\text{fuel mach.}i} \) = Energy consumption by fuel machinery per work unit \( \left( \frac{kWh}{\text{work unit}} \right) \)

\( P_{\text{fuel mach.}k} \) = Fuel average power for each k machine \( (kW) \)

\( OT_{\text{fuel mach.}k} \) = Operation time of fuel for each k machine \( \left( \frac{h}{\text{work unit}} \right) \)

Then, emissions can be calculated as follows:

\[
E_{\text{fuel mach.}i} \left( \frac{kg \ CO_2e}{\text{work unit}} \right) = \sum_k \left[ EC_{\text{fuel mach.}k} \left( \frac{kWh}{\text{work unit}} \right) \cdot EF_{\text{fuel,k}} \left( \frac{kg \ CO_2e}{kWh} \right) \right]
\]  

Equation 2.4

Where:

\( E_{\text{fuel mach.}i} \) = Emissions by fuel machinery per work unit \( \left( \frac{kg \ CO_2e}{\text{work unit}} \right) \)

\( EF_{\text{fuel,k}} \) = Emission factor considered fuel in the k machine \( \left( \frac{kg \ CO_2e}{kWh} \right) \)

Total for a work unit

Total energy consumption by machinery used in a work unit is calculated by adding values previously calculated for electric and fuel machinery:

\[
EC_{\text{mach.}i} \left( \frac{kWh}{\text{work unit}} \right) = EC_{\text{elec. mach.}i} \left( \frac{kWh}{\text{work unit}} \right) + EC_{\text{fuel mach.}i} \left( \frac{kWh}{\text{work unit}} \right)
\]  

Equation 2.5

Where:

\( EC_{\text{mach.}i} \) = Energy consumption by machinery per work unit \( \left( \frac{kWh}{\text{work unit}} \right) \)
In the same way, emissions from the same work unit can be calculated as follows:

\[
E_{\text{mach. } i} \left( \frac{\text{kg} \ CO_2e}{\text{work unit}} \right) = E_{\text{elec. } \text{mach. } i} \left( \frac{\text{kg} \ CO_2e}{\text{work unit}} \right) + E_{\text{fuel } \text{mach. } i} \left( \frac{\text{kg} \ CO_2e}{\text{work unit}} \right)
\]

Where:

\[E_{\text{mach. } i} = \text{Emissions by machinery per work unit} \left( \frac{\text{kg} \ CO_2e}{\text{work unit}} \right)\]

**Total for a size unit of a drainage system**

Total energy consumption by machinery used in the construction of a size unit of a drainage system is calculated by multiplying values previously calculated for each work unit by the quantity of the work unit determined for a size unit of the drainage system:

\[
UEC_{\text{mach. DRAINAGE SYSTEM}} \left( \frac{\text{kWh}}{\text{size unit}} \right) = \sum_i \left[ E_{\text{mach. } i} \left( \frac{\text{kWh}}{\text{work unit}} \right) \cdot Q_i \left( \frac{\text{work unit}}{\text{size unit}} \right) \right]
\]

Where:

\[UEC_{\text{mach. DRAINAGE SYSTEM}} = \text{Total Energy consumption by machinery per Unitary size of a drainage system} \left( \frac{\text{kWh}}{\text{size unit}} \right)\]

\[Q_i = \text{Quantity of work unit per unitary size of a drainage system} \left( \frac{\text{work unit}}{\text{size unit}} \right)\]

In the same way, unitary emissions from the same drainage systems can be calculated as follows:

\[
UE_{\text{mach. DRAINAGE SYSTEM}} \left( \frac{\text{kg} \ CO_2e}{\text{size unit}} \right) = \sum_i \left[ E_{\text{mach. } i} \left( \frac{\text{kg} \ CO_2e}{\text{work unit}} \right) \cdot Q_i \left( \frac{\text{work unit}}{\text{size unit}} \right) \right]
\]

Where:

\[UE_{\text{mach. DRAINAGE SYSTEM}} = \text{Emissions by machinery per Unitary size of a drainage system} \left( \frac{\text{kg} \ CO_2e}{\text{size unit}} \right)\]
Total for a drainage system

Total energy consumption by machinery used in the construction of a drainage system is calculated by multiplying energy consumption by unitary size by the size of the drainage system:

\[
EC_{\text{mach. DRAINAGE SYSTEM}} (kWh) = UEC_{\text{mach. DRAINAGE SYSTEM}} \left(\frac{kWh}{\text{size unit}}\right) \cdot S_{\text{DRAINAGE SYSTEM}} \text{ (size unit)}
\]

Equation 2.9

Where:

\[
EC_{\text{mach. DRAINAGE SYSTEM}} = \text{Energy consumption by machinery used in the construction of a drainage system (kWh)}
\]

\[
S_{\text{DRAINAGE SYSTEM}} = \text{size of the drainage system (size unit)}
\]

In the same way, emissions from machinery used in the construction of the same drainage systems can be calculated as follows:

\[
E_{\text{mach. DRAINAGE SYSTEM}} (kg CO_2e) = UE_{\text{mach. DRAINAGE SYSTEM}} \left(\frac{kg CO_2e}{\text{size unit}}\right) \cdot S_{\text{DRAINAGE SYSTEM}} \text{ (size unit)}
\]

Equation 2.10

Where:

\[
E_{\text{mach. DRAINAGE SYSTEM}} = \text{Emissions by machinery used in the construction of a drainage system (kg CO}_2e\text{)}
\]

2.2.2. Materials

In this case material unit coincides with work unit.

Unlike machinery, total energy consumption from manufacturing processes of a material are calculated first, and then electric and fuel energy consumption.
Total energy consumption for a work unit

Energy factor of a material is defined as the amount of energy consumed in the production of one unit of material (a work unit). It is expressed as kWh per material unit (per work unit). It depends on two factors:

- **Material embodied energy**: Is defined as the total primary energy consumed from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate (ICE, 2011). Embodied energy values are given by inventories such *The Inventory of Carbon and Energy* (ICE, 2011) and their units are usually MJ per kg of material.

Embodied energy values include **feedstock**, which is defined as energy derived from fuel inputs that have been used as a material rather than a fuel. For example, petrochemicals may be used as feedstock materials to make plastics and rubber (ICE, 2011).

In this methodology, feedstock will be subtracted from embodied energy as the main object is to calculate separately electric and fuel energy used in the manufacturing processes of each material used in the construction of a drainage system.

- **Material density**: mass contained per unit of material (work unit).

Energy consumption factor of a material (work unit) is therefore calculated as follows:

\[
ECF_{\text{material}} \left( \frac{\text{kWh}}{\text{material unit}} \right) = EE_{\text{material}} \left( \frac{\text{MJ}}{\text{kg}} \right) \cdot \frac{1 \text{ kWh}}{3.6 \text{ MJ}} \cdot D_{\text{material}} \left( \frac{\text{kg}}{\text{material unit}} \right)
\]

*Equation 2.11*

Where:

\[
ECF_{\text{material}} = \text{Energy Consumption Factor of a material} \left( \frac{\text{kWh}}{\text{material unit}} \right)
\]

\[
EE_{\text{material}} = \text{Material Embodied Energy} \left( \frac{\text{MJ}}{\text{kg}} \right)
\]

\[
D_{\text{material}} = \text{Material Density} \left( \frac{\text{kg}}{\text{material unit}} \right)
\]

To continue, next two sections provide a description of the method for estimating energy consumption and CO₂ emissions of each material manufacturing processes, divided in electric and fuel energy.
Electricity for a work unit (in material production processes)

Electricity used in manufacturing processes of a material can be calculated by multiplying the total energy consumption in those processes by the electricity share in the industry, which can be found in sectorial reports or bibliography (ICE, 2011).

Electric energy consumption factor of a material (work unit) is calculated as follows:

\[
ECF_{\text{elect-material}} \left( \frac{kWh}{\text{material unit}} \right) = ECF_{\text{material}} \left( \frac{kWh}{\text{material unit}} \right) \cdot ES_{\text{material}} \left( \% \right) \frac{100}{100} \quad \text{Equation 2.12}
\]

Where:

\[
ECF_{\text{elect-material}} = \text{Electric Energy Consumption Factor of a material} \left( \frac{kWh}{\text{material unit}} \right)
\]

\[
ES_{\text{material}} = \text{Electricity share in the manufacturing industry of the material} \left( \% \right)
\]

Then, emissions from electric energy used in manufacturing of the same material unit (work unit) can be calculated as follows:

\[
E_{\text{elect-material}} \left( \frac{kg \ CO_2e}{\text{material unit}} \right) = ECF_{\text{elect-material}} \left( \frac{kWh}{\text{material unit}} \right) \cdot EF_{\text{elec.count}} \left( \frac{kg \ CO_2e}{kWh} \right) \quad \text{Equation 2.13}
\]

Where:

\[
E_{\text{elect-material}} = \text{Emissions by electric processes used in the manufacturing of a material unit} \left( \frac{kg \ CO_2e}{\text{material unit}} \right)
\]

\[
EF_{\text{elec.count.}} = \text{Emission factor for electricity production of a country or region} \left( \frac{kg \ CO_2e}{kWh} \right)
\]
Fuel for a work unit (in material production processes)

Fuel energy factor of a material (work unit) is calculated as follows:

\[
ECF_{\text{fuel,material}} \left( \frac{kWh}{\text{material unit}} \right) = ECF_{\text{material}} \left( \frac{kWh}{\text{material unit}} \right) \cdot \frac{FS_{\text{material}}}{100}
\]

\text{Equation 2.14}

Where:

\[
ECF_{\text{fuel,material}} = \text{Electric Energy Consumption Factor of a material} \left( \frac{kWh}{\text{material unit}} \right)
\]

\[
FS_{\text{material}} = \text{Fuel share in the manufacturing industry of the material} \left( \% \right)
\]

Then, emissions from fuel energy used in manufacturing of the same material unit (work unit) can be calculated as follows:

\[
E_{\text{fuel,material}} \left( \frac{kg \ CO_2e}{\text{material unit}} \right) = ECF_{\text{fuel,material}} \left( \frac{kWh}{\text{material unit}} \right) \cdot EF_{\text{fuel}} \left( \frac{kg \ CO_2e}{kWh} \right)
\]

\text{Equation 2.15}

Where:

\[
E_{\text{elect,material}} = \text{Emissions by fuel processes in the manufacturing of a material unit} \left( \frac{kg \ CO_2e}{\text{material unit}} \right)
\]

\[
EF_{\text{fuel}} = \text{Emission factor for for considered fuel} \left( \frac{kg \ CO_2e}{kWh} \right)
\]

Total emissions for a work unit (in material production processes)

Then, emissions from energy used in manufacturing of a material unit (work unit) can be calculated as follows:

\[
E_{\text{material}} \left( \frac{kg \ CO_2e}{\text{material unit}} \right) = E_{\text{elect,material}} \left( \frac{kg \ CO_2e}{\text{material unit}} \right) + E_{\text{fuel,material}} \left( \frac{kg \ CO_2e}{\text{material unit}} \right)
\]

\text{Equation 2.16}
Total for a size unit of a drainage system

Total energy consumption by manufacturing processes for material used in the construction of a unitary drainage system is calculated as shown below:

\[
U_{EC_{\text{material} \text{ DRAINAGE SYSTEM}}} \left( \frac{kWh}{\text{size unit}} \right) = \sum \left[ E_{\text{material}} \left( \frac{kWh}{\text{material unit}} \right) \cdot Q_{\text{material}} \left( \frac{\text{material unit}}{\text{size unit}} \right) \right]
\]

Equation 2.17

Where:

\[
U_{EC_{\text{material} \text{ DRAINAGE SYSTEM}}} = \text{Energy consumption in material manufacturing per Unitary size of a drainage system} \left( \frac{kWh}{\text{size unit}} \right)
\]

\[
Q_i = \text{Quantity of a material per unitary size of a drainage system} \left( \frac{\text{material unit}}{\text{size unit}} \right)
\]

In the same way, unitary emissions from the same drainage systems can be calculated as follows:

\[
U_{E_{\text{material} \text{ DRAINAGE SYSTEM}}} \left( \frac{\text{kg CO}_2e}{\text{size unit}} \right) = \sum \left[ E_{\text{material}} \left( \frac{\text{kg CO}_2e}{\text{material unit}} \right) \cdot Q_{\text{material}} \left( \frac{\text{material unit}}{\text{size unit}} \right) \right]
\]

Equation 2.18

Where:

\[
U_{E_{\text{material} \text{ DRAINAGE SYSTEM}}} = \text{Emissions in material manufacturing per Unitary size of a drainage system} \left( \frac{\text{kg CO}_2e}{\text{size unit}} \right)
\]
Total for a drainage system

Total energy consumption by manufacturing of material used in the construction of a drainage system is calculated by multiplying energy consumption by unitary size by the size of the drainage system:

\[
EC_{\text{material DRAINAGE SYSTEM}} (\text{kWh}) = UEC_{\text{material DRAINAGE SYSTEM}} \left( \frac{\text{kWh}}{\text{size unit}} \right) \cdot S_{\text{DRAINAGE SYSTEM}} (\text{size unit})
\]

Equation 2.19

Where:

\[
EC_{\text{material DRAINAGE SYSTEM}} = \text{Energy consumption in material manufacturing used in the construction of a drainage system (kWh)}
\]

\[
S_{\text{DRAINAGE SYSTEM}} = \text{size of the drainage system (size unit)}
\]

In the same way, emissions from manufacturing of materials used in the construction of the same drainage systems can be calculated as follows:

\[
E_{\text{material DRAINAGE SYSTEM}} (\text{kg CO}_2\text{e}) = UE_{\text{material DRAINAGE SYSTEM}} \left( \frac{\text{kg CO}_2\text{e}}{\text{size unit}} \right) \cdot S_{\text{DRAINAGE SYSTEM}} (\text{size unit})
\]

Equation 2.20

Where:

\[
E_{\text{material DRAINAGE SYSTEM}} = \text{Emissions in material manufacturing of construction of a drainage system (kg CO}_2\text{e)}
\]

Same methodology can be used for both conventional and sustainable drainage systems.
2.2.3. Total Construction

Total energy consumption in the construction of a drainage system is calculated as follows:

\[
EC_{\text{Construction}}^{\text{DRAINAGE SYSTEM}} (kW\cdot h) = EC_{\text{mach.}}^{\text{DRAINAGE SYSTEM}} (kW\cdot h) + EC_{\text{material}}^{\text{DRAINAGE SYSTEM}} (kW\cdot h)
\]  

Where:

\[
EC_{\text{Construction}}^{\text{DRAINAGE SYSTEM}} = \text{Energy consumption in the construction of a drainage system} (kW\cdot h)
\]

In the same way, emissions in the construction of a drainage system can be calculated as follows:

\[
E_{\text{Construction}}^{\text{DRAINAGE SYSTEM}}^{\text{CO}_2e} (kg) = E_{\text{mach.}}^{\text{DRAINAGE SYSTEM}}^{\text{CO}_2e} (kg) + E_{\text{material}}^{\text{DRAINAGE SYSTEM}}^{\text{CO}_2e} (kg)
\]  

Where:

\[
E_{\text{Construction}}^{\text{DRAINAGE SYSTEM}}^{\text{CO}_2e} = \text{Emissions in the construction of a drainage system} (kg)
\]
2.3. MAINTENANCE’S ENERGY CONSUMPTION CALCULATION METHOD

2.3.1. Annual Maintenance

Annual Maintenance refers to all activities carried out over the period of one year. These activities are simple and easy to execute. Inspection and monitoring are common for all drainage systems while other annual maintenance activities depend on each system characteristics. Some typical maintenance activities are: grass mowing and cuttings, litter removal, scrub clearance, weed control, vacuum sweeping of paving, top-up mulched areas / re-mulch beds as required, etc.

The methodology in annual maintenance includes the energy consumption and emissions associated to transport, that is the fuel consumed by the vehicle when visiting the site. It does not include the fuel consumption associated to perform any maintenance tasks (e.g. fuel used by the machinery such as for grass cutting).

In order to estimate the energy consumption and emission due to transport, a typical distance and number of trips per year for each drainage system is defined in Table 2.4. It must be highlighted that these values are based on literature, and therefore don’t represent specific cases, as they are strongly related to the climatic conditions of the area. For example, “Litter picking and grass cutting” are key maintenance activities and are normally the most frequent activities carried out, therefore it dictates the number of visits to site. In the UK, this can range from 6 to 24 cut per annum and just 2 trips would not be enough. Hence, it is recommended to analyse case by case these default values when real results are desired.

Moreover, additional assumptions are made in the methodology with the trip information data, such as fuel consumption per km, fuel energy content and associated emissions per trip. As default values, the followed data is considered:

- Typical transport distance ($d_{trip}$) of 5 km (representative of a round trip urban distance)
- Vehicle fuel consumption of 8 liter of diesel every 100 km (considering 10.03 kWh/liter and 2.68 kg CO$_2$/liter).
- Number of trips per year considered for Annual Maintenance are provided in the Table 2.4:
Hence, energy consumption in the annual maintenance of a drainage system is therefore calculated as follows:

\[
EC_{\text{ann.maint. \ DRAINAGE SYSTEM}}(\text{kWh/year}) = FC_{\text{vehicle}}(\text{l fuel/km}) \cdot d_{\text{trip}}(\text{km/trip}) \cdot N_{\text{trips}}(\text{trip/year}) \cdot ENF_{\text{fuel}}(\text{kWh/l fuel})
\]

Equation 2.23

Where:

\(EC_{\text{ann.maint. \ DRAINAGE SYSTEM}}\) = Energy consumption in the annual maintenance of a drainage system (kWh/year)

\(FC_{\text{vehicle}}\) = Vehicle fuel consumption (l fuel/km)

\(N_{\text{trips}}\) = Annual number of trips (trip/year)

\(ENF_{\text{fuel}}\) = Fuel energy factor (kWh/l fuel)
\[ d_{\text{trip}} = \text{Typical Distance covered per trip} \left( \frac{\text{km}}{\text{trip}} \right) \]

Typical distance covered per trip, \(d_{\text{trip}}\), is defined as the total distance of a round-trip when visiting one drainage system. In case of visiting more than one in the same round-trip, the typical distance per drainage system will be estimated as the total distance travelled divided by the number of drainage systems inspected.

In the same way, annual maintenance emissions only depend on the fuel consumed in travelling and it is calculated as follows:

\[
E_{\text{ann.maint. DRAINAGE SYSTEM}} = FC_{\text{vehicle}} \left( \frac{\text{kg CO}_2\text{e}}{\text{km}} \right) \cdot \frac{1}{d_{\text{trip}}} \cdot N_{\text{trips}} \cdot EF_{\text{fuel}} \left( \frac{\text{kg CO}_2\text{e}}{\text{l fuel}} \right) \]

Equation 2.24

Where:

\[
E_{\text{ann.maint. DRAINAGE SYSTEM}} = \text{Emissions in the annual maintenance of a drainage system} \left( \frac{\text{kg CO}_2\text{e}}{\text{year}} \right)
\]

\[
EF_{\text{fuel}} = \text{Fuel emission factor} \left( \frac{\text{kg CO}_2\text{e}}{\text{l fuel}} \right)
\]

2.3.2. Periodic Maintenance

Periodic Maintenance refers to all those activities carried out every several years (see Table 2.5). Examples of scheduled periodic maintenance activities include: clear vegetation, de-silting, de-silting of main area, install new geotextile, remove and reinstall block pavement, and remove, dispose and replace gravel layer. These activities are (generally) more difficult to execute than the annual maintenance activities and are, consequently, more energetically intensive.

Periodic maintenance activities are difficult to forecast without historical information and given the relevant infancy of SUDS this is an area where additional research is still required. In this methodology, emission factor in kg CO\(_2\)e/unit for these activities and their frequency were obtained from relevant literature, such as the Scottish tool for SuDS cost assessment “SUDS for Roads Whole Life Cost tool” (SUDSWP and SCOTS, 2012). Table 2.5 and Table 2.6 include the Emission (EF) and Energy Factors (ENF) per task unit (m\(^3\) excavation, m\(^2\) geotextile, etc.)

Unit is different depending on the activity: m of swale for vegetation clearing, m\(^3\) of sediments for de-silting and main area of ponds, basin and wetlands, m\(^2\) of top area of filter drain, infiltration trenches or soakaways for installation of new geotextile, m\(^2\) of pavement for removal and reinstalltion of block
pavement and $m^3$ of gravel layer for replacement of gravel layer in filter drain, infiltration trenches and soakaways. Therefore, quantities of previous units are linked to the design parameters of drainage systems.

<table>
<thead>
<tr>
<th>DRAINAGE SYSTEM</th>
<th>PERIODIC MAINTENANCE TASK</th>
<th>EF, UNITS</th>
<th>EF, VALUE</th>
<th>FREQ., YEARS</th>
<th>EF, YEAR EQUIV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewer Pipes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Pavement</td>
<td>&gt;&gt; Remove and reinstall block pavement and install new geotextile</td>
<td>(kgCO₂e/m²)</td>
<td>0.5</td>
<td>25</td>
<td>0.020</td>
</tr>
<tr>
<td>Structural Detention Facilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional Roof</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetated Swales</td>
<td>&gt;&gt; Clear vegetation from swale &amp; dispose of arisings off site</td>
<td>(kgCO₂e/m)</td>
<td>0.395</td>
<td>5</td>
<td>0.079</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; De-silting of swale</td>
<td>(kgCO₂e/m)</td>
<td>1.755</td>
<td>5</td>
<td>0.351</td>
</tr>
<tr>
<td>Filter Drains</td>
<td>&gt;&gt; Remove, dispose and replace top gravel layer</td>
<td>(kgCO₂e/m²)</td>
<td>13.57</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; Install new geotextile</td>
<td>(kgCO₂e/m²)</td>
<td>2.73</td>
<td>5</td>
<td>0.546</td>
</tr>
<tr>
<td>Infiltration trenches</td>
<td>&gt;&gt; Remove, dispose and replace top gravel layer</td>
<td>(kgCO₂e/m²)</td>
<td>13.57</td>
<td>5</td>
<td>2.714</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; Install new geotextile</td>
<td>(kgCO₂e/m²)</td>
<td>2.73</td>
<td>5</td>
<td>0.546</td>
</tr>
<tr>
<td>Soakaways</td>
<td>&gt;&gt; Remove, dispose and replace top gravel layer</td>
<td>(kgCO₂e/m²)</td>
<td>13.57</td>
<td>5</td>
<td>2.714</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; Install new geotextile</td>
<td>(kgCO₂e/m²)</td>
<td>2.73</td>
<td>5</td>
<td>0.546</td>
</tr>
<tr>
<td>Filter Strips</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeable Pavement</td>
<td>&gt;&gt; Remove and reinstall block pavement and install new geotextile</td>
<td>(kgCO₂e/m²)</td>
<td>1.84</td>
<td>25</td>
<td>0.074</td>
</tr>
<tr>
<td>Retention Ponds</td>
<td>&gt;&gt; De-silting &amp; dispose sediments off site</td>
<td>(kgCO₂e/m³)</td>
<td>4.57</td>
<td>5</td>
<td>0.914</td>
</tr>
<tr>
<td>Detention Basins</td>
<td>&gt;&gt; De-silting &amp; dispose sediments off site</td>
<td>(kgCO₂e/m³)</td>
<td>4.57</td>
<td>5</td>
<td>0.914</td>
</tr>
<tr>
<td>Infiltration Basins</td>
<td>&gt;&gt; De-silting &amp; dispose sediments off site</td>
<td>(kgCO₂e/m³)</td>
<td>4.57</td>
<td>5</td>
<td>0.914</td>
</tr>
<tr>
<td>Rain gardens</td>
<td>&gt;&gt; Removal and replacement of silt covered vegetation</td>
<td>(kgCO₂e/m³)</td>
<td>0.13</td>
<td>5</td>
<td>0.026</td>
</tr>
<tr>
<td>Bioretention areas</td>
<td>&gt;&gt; Removal and replacement of silt covered vegetation</td>
<td>(kgCO₂e/m³)</td>
<td>0.13</td>
<td>5</td>
<td>0.026</td>
</tr>
<tr>
<td>Constructed Wetlands</td>
<td>&gt;&gt; De-silting of forebay &amp; dispose sediments off site</td>
<td>(kgCO₂e/m³)</td>
<td>4.57</td>
<td>5</td>
<td>0.914</td>
</tr>
<tr>
<td>Complex Rainwater Harvesting System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water butts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Roof</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geocellular Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5. Emission Factors for each maintenance task. Source: Prepared by the authors based on the tool “SUDS for Roads Whole Life Cost tool” (SUDSWP and SCOTS, 2012).
### Table 2.6. Energy Factors for each drainage system. Source: Prepared by the authors.

<table>
<thead>
<tr>
<th>DRAINAGE SYSTEM</th>
<th>PERIODIC MAINTENANCE TASK</th>
<th>ENF, UNITS</th>
<th>ENF, VALUE</th>
<th>FREQ., YEARS</th>
<th>ENF, YEAR EQUIV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewer Pipes</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Pavement</td>
<td>&gt;&gt; Remove and reinstall block pavement and install new geotextile (kWh/m²)</td>
<td>0.132</td>
<td>25</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Structural Detention Facilities</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional Roof</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetated Swales</td>
<td>&gt;&gt; Clear vegetation from swale &amp; dispose of arisings off site (kWh/m)</td>
<td>1.500</td>
<td>5</td>
<td>0.300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; De-silting of swale (kWh/m)</td>
<td>6.661</td>
<td>5</td>
<td>1.332</td>
<td></td>
</tr>
<tr>
<td>Filter Drains</td>
<td>&gt;&gt; Remove, dispose and replace top gravel layer (kWh/m³)</td>
<td>51.505</td>
<td>5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; Install new geotextile (kWh/m³)</td>
<td>10.362</td>
<td>5</td>
<td>2.072</td>
<td></td>
</tr>
<tr>
<td>Infiltration trenches</td>
<td>&gt;&gt; Remove, dispose and replace top gravel layer (kWh/m³)</td>
<td>51.505</td>
<td>5</td>
<td>10.301</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; Install new geotextile (kWh/m³)</td>
<td>10.362</td>
<td>5</td>
<td>2.072</td>
<td></td>
</tr>
<tr>
<td>Soakaways</td>
<td>&gt;&gt; Remove, dispose and replace top gravel layer (kWh/m³)</td>
<td>51.505</td>
<td>5</td>
<td>10.301</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;&gt; Install new geotextile (kWh/m³)</td>
<td>10.362</td>
<td>5</td>
<td>2.072</td>
<td></td>
</tr>
<tr>
<td>Filter Strips</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeable Pavement</td>
<td>&gt;&gt; Remove and reinstall block pavement and install new geotextile (kWh/m³)</td>
<td>6.984</td>
<td>25</td>
<td>0.279</td>
<td></td>
</tr>
<tr>
<td>Retention Ponds</td>
<td>&gt;&gt; De-silting &amp; dispose sediments off site (kWh/m³)</td>
<td>17.346</td>
<td>5</td>
<td>3.469</td>
<td></td>
</tr>
<tr>
<td>Detention Basins</td>
<td>&gt;&gt; De-silting &amp; dispose sediments off site (kWh/m³)</td>
<td>17.346</td>
<td>5</td>
<td>3.469</td>
<td></td>
</tr>
<tr>
<td>Infiltration Basins</td>
<td>&gt;&gt; De-silting &amp; dispose sediments off site (kWh/m³)</td>
<td>17.346</td>
<td>5</td>
<td>3.469</td>
<td></td>
</tr>
<tr>
<td>Rain gardens</td>
<td>&gt;&gt; Removal and replacement of silt covered vegetation (kWh/m³)</td>
<td>0.493</td>
<td>5</td>
<td>0.099</td>
<td></td>
</tr>
<tr>
<td>Bioretention areas</td>
<td>&gt;&gt; Removal and replacement of silt covered vegetation (kWh/m³)</td>
<td>0.493</td>
<td>5</td>
<td>0.099</td>
<td></td>
</tr>
<tr>
<td>Constructed Wetlands</td>
<td>&gt;&gt; De-silting of forebay &amp; dispose sediments off site (kWh/m³)</td>
<td>17.346</td>
<td>5</td>
<td>3.469</td>
<td></td>
</tr>
<tr>
<td>Complex Rainwater Harvesting System</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water butts</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Roof</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geocellular Systems</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From emission factor in kg CO₂e/unit, annual frequency of periodic maintenance activities and size, annual emissions can be calculated for each activity as follows:
\[ E_{\text{perio.maint.act.}} \left( \frac{\text{kg} \ CO_2 \text{e}}{\text{year}} \right) = EF_{\text{perio.maint.act.}} \left( \frac{\text{kg} \ CO_2 \text{e}}{\text{unit}} \right) \cdot Q_{\text{perio.maint.act.}} \left( \frac{\text{unit}}{\text{timemaint.act.}} \right) \cdot f_{\text{perio.maint.act.}} \left( \frac{\text{times}}{\text{year}} \right) \]  

Equation 2.25

Where:

\( E_{\text{per.maint.act.}} \) = Annual emissions in a periodic maintenance activity \( \left( \frac{\text{kg} \ CO_2 \text{e}}{\text{year}} \right) \)

\( EF_{\text{act.}} \) = Emission factor of a periodic maintenance activity \( \left( \frac{\text{kg} \ CO_2 \text{e}}{\text{unit}} \right) \)

\( Q_{\text{act.}} \) = Quantity for the parameter used in \( EF_{\text{act.}} \) (unit)

\( f_{\text{perio.maint.act.}} \) = annual frequency of a periodic maintenance activity \( \left( \frac{\text{times}}{\text{year}} \right) \)

Annual emission in the periodic maintenance of a drainage system is, therefore, calculated by adding emissions from all maintenance activities it needs:

\[ E_{\text{perio.maint.DRAINAGE SYSTEM}} \left( \frac{\text{kg} \ CO_2 \text{e}}{\text{year}} \right) = \sum E_{\text{perio.maint.act.}} \left( \frac{\text{kg} \ CO_2 \text{e}}{\text{year}} \right) \]  

Equation 2.26

Where:

\( E_{\text{perio.maint.DRAINAGE SYSTEM}} \) = Annual emissions in the periodic maintenance of a drainage system \( \left( \frac{\text{kg} \ CO_2 \text{e}}{\text{year}} \right) \)

Annual energy consumption in the periodic maintenance of a drainage system is calculated from annual emissions and emission factor of the considered energy source:
\[
EC_{\text{perio.maint.}}^{\text{DRAINAGE SYSTEM}} \left( \frac{kWh}{\text{year}} \right) = \frac{E_{\text{perio.maint.}}^{\text{DRAINAGE SYSTEM}} \left( \frac{\text{kg CO}_2\text{e}}{\text{year}} \right)}{EF_{\text{ener.sour.}} \left( \frac{\text{kg CO}_2\text{e}}{\text{kWh}} \right)}
\]  
*Equation 2.27*

Where:

\[
EC_{\text{perio.maint.}}^{\text{DRAINAGE SYSTEM}} = \text{Annual energy consumption in the periodic maintenance of a drainage system} \left( \frac{kWh}{\text{year}} \right)
\]

\[
EF_{\text{ener.sour.}} = \text{Emission factor of the considered energy source} \left( \frac{\text{kg CO}_2\text{e}}{\text{kWh}} \right)
\]

### 2.3.3. Total Maintenance

Annual energy consumption in the maintenance of a drainage system is therefore calculated by considering both annual and periodic maintenances:

\[
EC_{\text{Maintenance}}^{\text{DRAINAGE SYSTEM}} \left( \frac{kWh}{\text{year}} \right) = EC_{\text{ann.maint.}}^{\text{DRAINAGE SYSTEM}} \left( \frac{kWh}{\text{year}} \right) + EC_{\text{perio.maint.}}^{\text{DRAINAGE SYSTEM}} \left( \frac{kWh}{\text{year}} \right)
\]  
*Equation 2.28*

Where:

\[
EC_{\text{Maintenance}}^{\text{DRAINAGE SYSTEM}} = \text{Annual energy consumption in the maintenance of a drainage system} \left( \frac{kWh}{\text{year}} \right)
\]

Similarly, annual emissions in the maintenance of a drainage system are calculated as follows:

\[
E_{\text{Maintenance}}^{\text{DRAINAGE SYSTEM}} \left( \frac{\text{kg CO}_2\text{e}}{\text{year}} \right) = E_{\text{ann.maint.}}^{\text{DRAINAGE SYSTEM}} \left( \frac{\text{kg CO}_2\text{e}}{\text{year}} \right) + E_{\text{perio.maint.}}^{\text{DRAINAGE SYSTEM}} \left( \frac{\text{kg CO}_2\text{e}}{\text{year}} \right)
\]  
*Equation 2.29*
Where:

\[
E_{\text{Maintenance, DRAINAGE SYSTEM}} = \text{Annual emissions in the maintenance of a drainage system (kg CO}_2\text{e/ year)}
\]
2.4. Datasheets

This section includes a relation of the different drainage systems studied. For each drainage system it is provided a relation of the design parameters assumed for calculations, and the coefficients for energy and CO₂ emissions in construction and operation and maintenance.

In the next datasheets it may be found the different drainage systems studied: Sustainable and Conventional.

Datasheets are structured as following:

- **Assumed design parameters**: mainly based on common practices obtained from literature. For this study main reference has been “SUDS for Roads Whole Life Cost tool” (SUDSWP and SCOTS, 2012).

- **Energy Consumption (kWh)**: Total energy consumption of electricity and fuel in construction activities. Main references have been “SUDS for Roads Whole Life Cost tool” (SUDSWP and SCOTS, 2012) and “The Inventory of Carbon and Energy” (ICE, 2011).

- **Emissions (kg CO₂e)**: Total emissions due to consumed electricity and fuel in construction activities. Main references have been “SUDS for Roads Whole Life Cost tool” (SUDSWP and SCOTS, 2012) and “The Inventory of Carbon and Energy” (ICE, 2011).

- **Construction**: Energy and emissions coefficients per unit size (i.e. kWh/m²) due to construction activities (Prepared by the authors). Indicators are obtained based on many premises; methodology used for their calculation is presented in Section 2.2.

- **Maintenance**: Energy and emissions coefficients per unit size (i.e. kWh/m²) associated to maintenance activities (Prepared by the authors). It includes Periodic and Annual Maintenance, which are obtained based on many premises. Take the time to review them in Section 2.3. One on the main considerations is the number of trips associated to each visit, which usually varies significantly depending on the local conditions (Example: visiting more than one site may reduce the energy and emissions associated to each drainage system).
2.4.1. Rain harvesting systems

Assumed design parameters:

- Estimated parameters for an average property:
  - 1 storage tank: 4,000 l
  - 50 m pipes
  - 1 pump
  - 1 trap

- Generally, it is used one per average property.
- Stored volume = 4 m$^3$

**Energy Consumption (kWh)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>77%</td>
<td>77%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>23%</td>
<td>23%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

- 982 kWh
- 3,534 MJ

**Emissions (kg CO$_2$e)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>81%</td>
<td>81%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>19%</td>
<td>19%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

- 322 kg CO$_2$e

**Construction**

- Coefficient for Energy Consumption in Construction: 245.42 kWh/m$^3$
- Coefficient for Emissions in Construction: 80.61 kgCO$_2$e/m$^3$

*Average Emission Factor: 0.33 kg CO$_2$e/kWh*

**Maintenance**

- Coefficient for Energy Consumption in Maintenance: 2.01 kWh/m$^3$
- Coefficient for Emissions in Maintenance: 0.54 kCO$_2$e/m$^3$
2.4.2. Water butts

**Assumed design parameters:**

Estimated parameters for an average property:

- 1 storage tank: 500 l volume
- Generally, it is used one per average property.
- Stored volume = 0.5 m³

**Energy Consumption (kWh)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>79%</td>
<td>79%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>21%</td>
<td>21%</td>
</tr>
<tr>
<td>Total</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

- 121 kWh
- 436 MJ

**Emissions (kg CO₂e)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>83%</td>
<td>83%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>17%</td>
<td>17%</td>
</tr>
<tr>
<td>Total</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

- 40 kg CO₂e

**Construction**

- Coefficient for Energy Consumption in Construction: 242 kWh/m³
- Coefficient for Emissions in Construction: 80 kgCO₂e/m³

**Average Emission Factor:** 0.33 kg CO₂e/kWh

**Maintenance**

- Coefficient for Energy Consumption in Maintenance: 16.01 kWh/m³
- Coefficient for Emissions in Maintenance: 4.29 kCO₂e/m³
2.4.3. Green roofs

**Assumed design parameters:**

Materials for 1 m² of an extensive inverted green roof ref. 15132A70 (ITeC, 2013):

- Foaming additive: 0,25 kg
- Water: 22,47 kg
- Aggregate: 131,34 kg
- Bitumen: 7,39 kg
- Cement: 24,54 kg
- Vegetation layer: 11,11 kg
- Polyester: 0,18 kg
- Polystyrene: 0,77 kg
- Extruded polystyrene: 1,58 kg
- Polyethylene: 0,15 kg
- Polypropylene: 0,45 kg

**Area = 1 m² of green roof**

### Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>43%</td>
<td>43%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>57%</td>
<td>57%</td>
</tr>
<tr>
<td>Total</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

- 93 kWh
- 336 MJ

### Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Total</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

- 28 kg CO₂e

### Construction

- Coefficient for Energy Consumption in Construction: 93 kWh/m²
- Coefficient for Emissions in Construction: 28 kgCO₂e/m²

**Average Emission Factor:** 0.30 kg CO₂e/kWh

### Maintenance

- Coefficient for Energy Consumption in Maintenance: 8.02 kWh/m²
- Coefficient for Emissions in Maintenance: 2.14 kCO₂e/m²
2.4.4. Permeable pavements

Assumed design parameters:

- Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).
  - Area of permeable block paving = 1 m²
  - Type of permeable block paving system = total infiltration
  - Outlet pipes required = No

Area = 1 m² of permeable pavement

Note: Area is referred to top area

Energy Consumption (kWh)

<table>
<thead>
<tr>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>62%</td>
</tr>
<tr>
<td>Fuel</td>
<td>8%</td>
<td>30%</td>
</tr>
<tr>
<td>Total</td>
<td>8%</td>
<td>92%</td>
</tr>
</tbody>
</table>

Total Energy Consumption: 92 kWh
332 MJ

Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>68%</td>
</tr>
<tr>
<td>Fuel</td>
<td>7%</td>
<td>25%</td>
</tr>
<tr>
<td>Total</td>
<td>7%</td>
<td>93%</td>
</tr>
</tbody>
</table>

Total Emissions: 29 kg CO₂e

Construction

Coefficient for Energy Consumption in Construction: 92 kWh/m²
Coefficient for Emissions in Construction: 29 kgCO₂e/m²

Average Emission Factor: 0.32 kg CO₂e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: 8.03 kWh/m²
Coefficient for Emissions in Maintenance: 2.14 kgCO₂e/m²
2.4.5. Soakaways

**Assumed design parameters:**

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Material of upper layer = soil
- Total depth= 2,1 m
- Width= 2 m
- Length= 2 m
- Number of Inlet structures = 0
- Number of outlet structures = 0
- Gravel strip to control sheet inflow = No
- Perforated collection pipes = No
- Liner to prevent infiltration = No
- Area = 4 m²
- Volume = 9 m³

*Note: Area is referred to top area (including freeboard). Volume includes freeboard*

### Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>62%</td>
<td>62%</td>
</tr>
<tr>
<td>Fuel</td>
<td>8%</td>
<td>30%</td>
<td>38%</td>
</tr>
<tr>
<td>Total</td>
<td>8%</td>
<td>92%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

92 kWh

332 MJ

### Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>68%</td>
<td>68%</td>
</tr>
<tr>
<td>Fuel</td>
<td>7%</td>
<td>25%</td>
<td>32%</td>
</tr>
<tr>
<td>Total</td>
<td>7%</td>
<td>93%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

29 kg CO₂e

### Construction

- Coefficient for Energy Consumption in Construction: 92 kWh/m³
- Coefficient for Emissions in Construction: 29 kgCO₂e/m³

*Average Emission Factor: 0.32 kg CO₂e/kWh*

### Maintenance

- Coefficient for Energy Consumption in Maintenance: 6.39 kWh/m³
- Coefficient for Emissions in Maintenance: 1.69 kCO₂e/m³
2.4.6. Infiltration trenches

**Assumed design parameters:**

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Material of upper layer = soil
- Total depth= 0,6 m
- Width= 0,3 m
- Length= 40 m
- Number of Inlet structures = 0
- Number of outlet structures = 0
- Gravel strip to control sheet inflow = Yes
  
  - Perforated collection pipes = No
  - Liner to prevent infiltration = No
  
  - Area = 12 m²
  - Volume = 9 m³

*Note: Area is referred to top area (including freeboard)*

*Volume includes freeboard*

### Energy Consumption (kWh)

<table>
<thead>
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<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td>0%</td>
<td>51%</td>
<td>51%</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>20%</td>
<td>29%</td>
<td>49%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>20%</td>
<td>80%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

502 kWh

1,806 MJ

### Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td>0%</td>
<td>57%</td>
<td>57%</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>18%</td>
<td>25%</td>
<td>43%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>18%</td>
<td>82%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

154 kg CO₂e

### Construction

- Coefficient for Energy Consumption in Construction: 56 kWh/m³
- Coefficient for Emissions in Construction: 17 kgCO₂e/m³

*Average Emission Factor: 0.31 kg CO₂e/kWh*

### Maintenance

- Coefficient for Energy Consumption in Maintenance: 7.78 kWh/m³
- Coefficient for Emissions in Maintenance: 2.05 kgCO₂e/m³
2.4.7. Geocellular systems

Assumed design parameters:

Estimated parameters for 1 m³ detention facility:

- Excavation: 1.3 m³
- Liner to prevent infiltration (if detention system): 5 m²
- Gate valves: 0,004
- Steel pipe: 0,02 m
- Pump: 0,5
- Modular Polypropylene Box: 45 kg

Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>72%</td>
<td>72%</td>
</tr>
<tr>
<td>Fuel</td>
<td>3%</td>
<td>25%</td>
<td>28%</td>
</tr>
<tr>
<td>Total</td>
<td>3%</td>
<td>97%</td>
<td></td>
</tr>
</tbody>
</table>

Total Energy Consumption: 1,012 kWh
3,643 MJ

Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>77%</td>
<td>77%</td>
</tr>
<tr>
<td>Fuel</td>
<td>2%</td>
<td>21%</td>
<td>23%</td>
</tr>
<tr>
<td>Total</td>
<td>2%</td>
<td>98%</td>
<td></td>
</tr>
</tbody>
</table>

Total Emissions: 329 kg CO₂e

Construction

Coefficient for Energy Consumption in Construction: 1012 kWh/unit
Coefficient for Emissions in Construction: 329 kgCO₂e/unit

Average Emission Factor: 0.32 kg CO₂e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: 8.02 kWh/unit
Coefficient for Emissions in Maintenance: 2.14 kCO₂e/unit
2.4.8. Bioretention areas

Assumed design parameters:

- Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).
- Width of bio-retention area = 10 m
- Inlet type = gravel buffer strip

- Area = 200 m²

Note: Area is referred to top area

Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>52%</td>
<td>52%</td>
</tr>
<tr>
<td>Fuel</td>
<td>21%</td>
<td>27%</td>
<td>48%</td>
</tr>
<tr>
<td>Total</td>
<td>21%</td>
<td>79%</td>
<td></td>
</tr>
</tbody>
</table>

Total Energy Consumption: 27,425 kWh 98,731 MJ

Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>59%</td>
<td>59%</td>
</tr>
<tr>
<td>Fuel</td>
<td>18%</td>
<td>23%</td>
<td>41%</td>
</tr>
<tr>
<td>Total</td>
<td>18%</td>
<td>82%</td>
<td></td>
</tr>
</tbody>
</table>

Total Emissions: 8,464 kg CO₂e

Construction

- Coefficient for Energy Consumption in Construction: 137 kWh/m²
- Coefficient for Emissions in Construction: 42 kg CO₂e/m²

Average Emission Factor: 0.31 kg CO₂e/kWh

Maintenance

- Coefficient for Energy Consumption in Maintenance: 0.34 kWh/m²
- Coefficient for Emissions in Maintenance: 0.09 kg CO₂e/m²
2.4.9. Rain gardens

Assumed design parameters:

- Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).
- Width of rain garden = 4 m
- Inlet type = gravel buffer strip
- Area = 32 m²

Note: Area is referred to top area

Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>48%</td>
<td>48%</td>
</tr>
<tr>
<td>Fuel</td>
<td>24%</td>
<td>28%</td>
<td>52%</td>
</tr>
<tr>
<td>Total</td>
<td>24%</td>
<td>76%</td>
<td></td>
</tr>
</tbody>
</table>

Total Energy Consumption: 3,776 kWh, 13,593 MJ

Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>54%</td>
<td>54%</td>
</tr>
<tr>
<td>Fuel</td>
<td>21%</td>
<td>25%</td>
<td>46%</td>
</tr>
<tr>
<td>Total</td>
<td>21%</td>
<td>79%</td>
<td></td>
</tr>
</tbody>
</table>

Total Emissions: 1,152 kg CO₂e

Construction

- Coefficient for Energy Consumption in Construction: 118 kWh/m²
- Coefficient for Emissions in Construction: 36 kgCO₂e/m²

Average Emission Factor: 0.30 kg CO₂e/kWh

Maintenance

- Coefficient for Energy Consumption in Maintenance: 1.60 kWh/m²
- Coefficient for Emissions in Maintenance: 0.43 kgCO₂e/m²
2.4.10. Filter strips

Assumed design parameters:

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Slope = 4 %
- Width = 7 m
- Length = 40 m
- Gravel strip to control sheet inflow = No
- Lined filter strip = No

**Area = 280 m²**

Note: Area is referred to top area

<table>
<thead>
<tr>
<th>Energy Consumption (kWh)</th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>33%</td>
<td>33%</td>
</tr>
<tr>
<td>Fuel</td>
<td>58%</td>
<td>9%</td>
<td>67%</td>
</tr>
<tr>
<td>Total</td>
<td>58%</td>
<td>42%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

- 3,244 kWh
- 11,667 MJ

<table>
<thead>
<tr>
<th>Emissions (kg CO₂e)</th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>39%</td>
<td>39%</td>
</tr>
<tr>
<td>Fuel</td>
<td>53%</td>
<td>8%</td>
<td>61%</td>
</tr>
<tr>
<td>Total</td>
<td>53%</td>
<td>47%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

- 951 kg CO₂e

**Construction**

- Coefficient for Energy Consumption in Construction: 12 kWh/m²
- Coefficient for Emissions in Construction: 3 kgCO₂e/m²

*Average Emission Factor: 0.29 kg CO₂e/kWh*

**Maintenance**

- Coefficient for Energy Consumption in Maintenance: 0.17 kWh/m²
- Coefficient for Emissions in Maintenance: 0.05 kgCO₂e/m²
2.4.11. Filter drains

**Assumed design parameters:**

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Material of upper layer = soil
- Total depth = 0.6 m
- Width = 0.3 m
- Length = 40 m
- Number of inlet structures = 0
- Number of outlet structures = 1
- Type of outlet structures = Bagwork
- Gravel strip to control sheet inflow = Yes
- Perforated collection pipes = Yes (1 m = 0.5 m at each end of the device)
- Liner to prevent infiltration = Yes (12 m²)
- Area = 12 m²
- Volume = 9 m³

*Note: Area is referred to top area (including freeboard). Volume includes freeboard*

---

**Energy Consumption (kWh)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td>0%</td>
<td>61%</td>
<td>61%</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>11%</td>
<td>28%</td>
<td>39%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>11%</td>
<td>89%</td>
<td></td>
</tr>
</tbody>
</table>

*Total Energy Consumption: 912 kWh, 3,281 MJ*

**Emissions (kg CO₂e)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td>0%</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>10%</td>
<td>23%</td>
<td>33%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>10%</td>
<td>90%</td>
<td></td>
</tr>
</tbody>
</table>

*Total Emissions: 288 kg CO₂e*

---

**Construction**

Coefficient for Energy Consumption in Construction: 101 kWh/m³

Coefficient for Emissions in Construction: 32 kgCO₂e/m³

*Average Emission Factor: 0.32 kg CO₂e/kWh*

---

**Maintenance**

Coefficient for Energy Consumption in Maintenance: 7.78 kWh/m³

Coefficient for Emissions in Maintenance: 2.05 kgCO₂e/m³
2.4.12. Vegetated swales

Assumed design parameters:

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Type of swale= enhanced dry swale
- Width= 3 m
- Length= 70 m
- Number of outlet structures = 1
- Type of outlet structure = Bagwork

- Area = 617 m²
- Volume = 207 m³

Note: Area is referred to top area

Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>58%</td>
<td>58%</td>
</tr>
<tr>
<td>Fuel</td>
<td>17%</td>
<td>25%</td>
<td>42%</td>
</tr>
<tr>
<td>Total</td>
<td>17%</td>
<td>83%</td>
<td></td>
</tr>
</tbody>
</table>

Total Energy Consumption: 26,403 kWh
95,050 MJ

Emissions (kg CO₂e)

<table>
<thead>
<tr>
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<th>Machinery</th>
<th>Materials</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>64%</td>
<td>64%</td>
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<tr>
<td>Fuel</td>
<td>15%</td>
<td>21%</td>
<td>36%</td>
</tr>
<tr>
<td>Total</td>
<td>15%</td>
<td>85%</td>
<td></td>
</tr>
</tbody>
</table>

Total Emissions: 8,271 kg CO₂e

Construction

Coefficient for Energy Consumption in Construction: 43 kWh/m²
Coefficient for Emissions in Construction: 13 kgCO₂e/m²

Average Emission Factor: 0.31 kg CO₂e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: 0.22 kWh/m²
Coefficient for Emissions in Maintenance: 0.06 kgCO₂e/m²
2.4.13. Infiltration basins

Assumed design parameters:

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Infiltration basin = Yes
- Bottom width of basin = 1,50 m
- Inlet channel to the basin = Yes
- Forebay = Yes
- Overflow channel = No
- Liner to prevent infiltration = No

- Area = 231 m²
- Volume = 462 m³

Note:

\[ \text{Area} = \frac{\text{Top area of basin (including freeboard)} + \text{Bottom area of basin}}{2} \]

Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>5%</td>
<td>5%</td>
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<tr>
<td>Fuel</td>
<td>93%</td>
<td>1%</td>
<td>95%</td>
</tr>
<tr>
<td>Total</td>
<td>93%</td>
<td>7%</td>
<td></td>
</tr>
</tbody>
</table>

Total Energy Consumption:

- 7,235 kWh
- 26,047 MJ

Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>7%</td>
<td>7%</td>
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<tr>
<td>Fuel</td>
<td>92%</td>
<td>1%</td>
<td>93%</td>
</tr>
<tr>
<td>Total</td>
<td>92%</td>
<td>8%</td>
<td></td>
</tr>
</tbody>
</table>

Total Emissions:

- 1,962 kg CO₂e

Construction

Coefficient for Energy Consumption in Construction: 16 kWh/m³
Coefficient for Emissions in Construction: 4 kgCO₂e/m³

Average Emission Factor: 0.27 kg CO₂e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: 0.02 kWh/m³
Coefficient for Emissions in Maintenance: 0.01 kgCO₂e/m³
2.4.14. Detention basins

Assumed design parameters:

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Infiltration basin = No (No = Detention Basin)
- Bottom width of basin = 1.50 m
- Inlet channel to the basin = No
- Forebay = Yes
- Overflow channel = No

- Area = 231 m$^2$
- Volume = 462 m$^3$

\[
\text{Area} = \frac{\text{Top area of basin (including freeboard)} + \text{Bottom area of basin}}{2}
\]

Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>34%</td>
<td>34%</td>
</tr>
<tr>
<td>Fuel</td>
<td>57%</td>
<td>9%</td>
<td>66%</td>
</tr>
<tr>
<td>Total</td>
<td>57%</td>
<td>43%</td>
<td></td>
</tr>
</tbody>
</table>

Total Energy Consumption: 11,790 kWh, 42,455 MJ

Emissions (kg CO$_2$e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Fuel</td>
<td>52%</td>
<td>8%</td>
<td>60%</td>
</tr>
<tr>
<td>Total</td>
<td>52%</td>
<td>48%</td>
<td></td>
</tr>
</tbody>
</table>

Total Emissions: 3,466 kg CO$_2$e

Construction

Coefficient for Energy Consumption in Construction: 26 kWh/m$^3$
Coefficient for Emissions in Construction: 7.5 kgCO$_2$e/m$^3$

Average Emission Factor: 0.29 kg CO$_2$e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: 0.02 kWh/m$^3$
Coefficient for Emissions in Maintenance: 0.01 kCO$_2$e/m$^3$
2.4.15. Retention ponds

**Assumed design parameters:**

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Bottom width of pond = 1.50m
- Forebay = Yes
- Type of inlet and outlet structures = Bagwork
- Overflow channel = No

- **Area** = 143 m²
- **Volume** = 286 m³

*Note:*

\[
\text{Area} = \frac{\text{Top area of basin (including freeboard)+Bottom area of basin}}{2}
\]

**Energy Consumption (kWh)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>43%</td>
<td>43%</td>
</tr>
<tr>
<td>Fuel</td>
<td>45%</td>
<td>12%</td>
<td>57%</td>
</tr>
<tr>
<td>Total</td>
<td>45%</td>
<td>55%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

- 10,574 kWh
- 38,067 MJ

**Emissions (kg CO₂e)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Fuel</td>
<td>52%</td>
<td>8%</td>
<td>60%</td>
</tr>
<tr>
<td>Total</td>
<td>52%</td>
<td>48%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

- 3,187 kg CO₂e

**Construction**

- Coefficient for Energy Consumption in Construction: 37 kWh/m³
- Coefficient for Emissions in Construction: 11 kgCO₂e/m³

*Average Emission Factor: 0.30 kg CO₂e/kWh*

**Maintenance**

- Coefficient for Energy Consumption in Maintenance: 0.03 kWh/m³
- Coefficient for Emissions in Maintenance: 0.01 kCO₂e/m³
2.4.16. Constructed wetlands

**Assumed design parameters:**

Recommended parameters for SUDS design are based on “SUDS for Roads Whole Life Cost tool” guide (SUDSWP and SCOTS, 2012).

- Bottom width of wetland = 1.5 m
- Inlet type = gravel buffer strip
- Forebay = Yes
- Overflow channel = No

- **Area** = 143 m²

**Note:**

\[
\text{Area} = \frac{\text{Top area of basin (including freeboard)}}{2} + \frac{\text{Bottom area of basin}}{2}
\]

**Energy Consumption (kWh)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>42%</td>
<td>42%</td>
</tr>
<tr>
<td>Fuel</td>
<td>46%</td>
<td>11%</td>
<td>58%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>46%</td>
<td>54%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**

- 10,277 kWh
- 36,998 MJ

**Emissions (kg CO₂e)**

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>49%</td>
<td>49%</td>
</tr>
<tr>
<td>Fuel</td>
<td>41%</td>
<td>10%</td>
<td>51%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>41%</td>
<td>59%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**

- 3,092 kg CO₂e

**Construction**

- Coefficient for Energy Consumption in Construction: **72 kWh/m²**
- Coefficient for Emissions in Construction: **11 kgCO₂e/m²**

*Average Emission Factor: 0.30 kg CO₂e/kWh*

**Maintenance**

- Coefficient for Energy Consumption in Maintenance: **0.07 kWh/m²**
- Coefficient for Emissions in Maintenance: **0.02 kCO₂e/m²**
Regarding **Conventional Drainage**, the following systems have been analyzed:

### 2.4.17. Sewer pipes

**Assumed design parameters:**

- Conventional drainage network
- Pipe Length: 900 m

#### Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>36%</td>
<td>36%</td>
</tr>
<tr>
<td>Fuel</td>
<td>43%</td>
<td>21%</td>
<td>64%</td>
</tr>
<tr>
<td>Total</td>
<td>43%</td>
<td>57%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**
- 28,800 kWh
- 103,680 MJ

#### Emissions (kg CO₂e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>42%</td>
<td>42%</td>
</tr>
<tr>
<td>Fuel</td>
<td>38%</td>
<td>19%</td>
<td>58%</td>
</tr>
<tr>
<td>Total</td>
<td>38%</td>
<td>62%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**
- 9,000 kg CO₂e

#### Construction

- Coefficient for Energy Consumption in Construction: 32 kWh/m
- Coefficient for Emissions in Construction: 10 kgCO₂e/m

**Average Emission Factor:** 0.30 kg CO₂e/kWh

#### Maintenance

- Coefficient for Energy Consumption in Maintenance: 4.01 kWh/m³
- Coefficient for Emissions in Maintenance: 1.07 kgCO₂e/m³
2.4.18. Standard pavement

Assumed design parameters:

- Conventional standard pavement
- \textbf{Area} = 1 m\(^2\) of pavement  
  \textit{Note: Area is referred to top area}


### Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>62%</td>
<td>62%</td>
</tr>
<tr>
<td>Fuel</td>
<td>2%</td>
<td>36%</td>
<td>38%</td>
</tr>
<tr>
<td>Total</td>
<td>2%</td>
<td>98%</td>
<td></td>
</tr>
</tbody>
</table>

\textit{Total Energy Consumption:}  
\hspace{1cm} 164 kWh  
\hspace{1cm} 590 MJ

### Emissions (kg CO\(_2\)e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>68%</td>
<td>68%</td>
</tr>
<tr>
<td>Fuel</td>
<td>1%</td>
<td>31%</td>
<td>32%</td>
</tr>
<tr>
<td>Total</td>
<td>1%</td>
<td>99%</td>
<td></td>
</tr>
</tbody>
</table>

\textit{Total Emissions:}  
\hspace{1cm} 52 kg CO\(_2\)e

### Construction

- Coefficient for Energy Consumption in Construction: 164 kWh/m\(^2\)
- Coefficient for Emissions in Construction: 52 kgCO\(_2\)e/m\(^2\)

\textit{Average Emission Factor:} 0.32 kg CO\(_2\)e/kWh

### Maintenance

- Coefficient for Energy Consumption in Maintenance: 4.01 kWh/m\(^2\)
- Coefficient for Emissions in Maintenance: 1.07 kgCO\(_2\)e/m\(^2\)
2.4.20. Structural detention facilities

Assumed design parameters:

- Conventional structural detention facility
- Area = 650 m$^3$

## Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>62%</td>
<td>62%</td>
</tr>
<tr>
<td>Fuel</td>
<td>5%</td>
<td>32%</td>
<td>38%</td>
</tr>
<tr>
<td>Total</td>
<td>5%</td>
<td>95%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Consumption:**
- 551,850 kWh
- 1986,660 MJ

## Emissions (kg CO$$_2$$e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>68%</td>
<td>68%</td>
</tr>
<tr>
<td>Fuel</td>
<td>4%</td>
<td>27%</td>
<td>32%</td>
</tr>
<tr>
<td>Total</td>
<td>4%</td>
<td>96%</td>
<td></td>
</tr>
</tbody>
</table>

**Total Emissions:**
- 3,466 kg CO$$_2$$e

## Construction

- Coefficient for Energy Consumption in Construction: 849 kWh/m$^3$
- Coefficient for Emissions in Construction: 269 kgCO$$_2$$e/m$^3$

*Average Emission Factor: 0.32 kg CO$$_2$$e/kWh*

## Maintenance

- Coefficient for Energy Consumption in Maintenance: 8.02 kWh/m$^3$
- Coefficient for Emissions in Maintenance: 2.14 kgCO$$_2$$e/m$^3$
### 2.4.21. Conventional roof

**Assumed design parameters:**

- Conventional roof
- Area = 1 m$^2$ of green roof

#### Energy Consumption (kWh)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>46%</td>
<td>46%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>54%</td>
<td>54%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0%</strong></td>
<td><strong>100%</strong></td>
<td><strong>Total Energy Consumption:</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>123 kWh</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>443 MJ</strong></td>
</tr>
</tbody>
</table>

#### Emissions (kg CO$_2$e)

<table>
<thead>
<tr>
<th></th>
<th>Machinery</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0%</td>
<td>52%</td>
<td>52%</td>
</tr>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>48%</td>
<td>48%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0%</strong></td>
<td><strong>100%</strong></td>
<td><strong>Total Emissions:</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>37 kg CO$_2$e</strong></td>
</tr>
</tbody>
</table>

#### Construction

- Coefficient for Energy Consumption in Construction: 123 kWh/m$^2$
- Coefficient for Emissions in Construction: 37 kgCO$_2$e/m$^2$

*Average Emission Factor: 0.30 kg CO$_2$e/kWh*

#### Maintenance

- Coefficient for Energy Consumption in Maintenance: 4.01 kWh/m$^2$
- Coefficient for Emissions in Maintenance: 1.07 kgCO$_2$e/m$^2$
3. **Water Distribution**

Total European freshwater resources related to population size are shown in the figure below. Finland, Sweden and Serbia recorded the highest freshwater annual resources per inhabitant (around 20000 m³ or more). By contrast, relatively low levels per inhabitant (below 3000 m³) were recorded in the six largest Member States (France, Italy, the United Kingdom, Spain, Germany and Poland), as well as in Romania, Belgium and the Czech Republic, with the lowest levels in Cyprus (405 m³ per inhabitant) and Malta (190 m³ per inhabitant).

![Fresh water resources graph](image)

*Figure 3.1. Long Term Average Annual Fresh Water Resources for some European Countries (EUROSTAT, 2013)*

Most EU Member States have annual rates of freshwater abstraction, surface and ground, between 50 m³ and 100 m³ per inhabitant as shown in the next table.

<table>
<thead>
<tr>
<th>Country</th>
<th>Fresh surface water abstraction (m³/inh-year)</th>
<th>Fresh ground water abstraction (m³/inh-year)</th>
<th>Fresh surface water abstraction (%)</th>
<th>Fresh ground water abstraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>70</td>
<td>46</td>
<td>34</td>
<td>66</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>132</td>
<td>62</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>70</td>
<td>33</td>
<td>54</td>
<td>46</td>
</tr>
<tr>
<td>Denmark</td>
<td>76</td>
<td>1</td>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>Germany</td>
<td>64</td>
<td>46</td>
<td>28</td>
<td>72</td>
</tr>
<tr>
<td>Estonia</td>
<td>44</td>
<td>21</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Ireland</td>
<td>148</td>
<td>39</td>
<td>74</td>
<td>26</td>
</tr>
<tr>
<td>Greece</td>
<td>77</td>
<td>21</td>
<td>73</td>
<td>27</td>
</tr>
<tr>
<td>Spain</td>
<td>132</td>
<td>34</td>
<td>74</td>
<td>26</td>
</tr>
</tbody>
</table>
Table 3.1. Average Annual (2002-2009) Fresh Water Abstraction by public water supply for some European countries (m³/inh-year) (EUROSTAT, 2013)

<table>
<thead>
<tr>
<th>Country</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>96</td>
<td>37</td>
<td>59</td>
<td>38</td>
<td>62</td>
</tr>
<tr>
<td>Croatia</td>
<td>113</td>
<td>14</td>
<td>99</td>
<td>13</td>
<td>87</td>
</tr>
<tr>
<td>Italy</td>
<td>153</td>
<td>22</td>
<td>131</td>
<td>14</td>
<td>86</td>
</tr>
<tr>
<td>Cyprus</td>
<td>61</td>
<td>29</td>
<td>33</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td>Lithuania</td>
<td>37</td>
<td>1</td>
<td>37</td>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>88</td>
<td>41</td>
<td>47</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td>Hungary</td>
<td>71</td>
<td>31</td>
<td>40</td>
<td>44</td>
<td>56</td>
</tr>
<tr>
<td>Malta</td>
<td>35</td>
<td>35</td>
<td>0</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>78</td>
<td>30</td>
<td>47</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>Austria</td>
<td>73</td>
<td>0</td>
<td>73</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Poland</td>
<td>55</td>
<td>18</td>
<td>37</td>
<td>32</td>
<td>68</td>
</tr>
<tr>
<td>Portugal</td>
<td>92</td>
<td>57</td>
<td>35</td>
<td>62</td>
<td>38</td>
</tr>
<tr>
<td>Romania</td>
<td>79</td>
<td>55</td>
<td>25</td>
<td>69</td>
<td>31</td>
</tr>
<tr>
<td>Slovenia</td>
<td>85</td>
<td>2</td>
<td>82</td>
<td>3</td>
<td>97</td>
</tr>
<tr>
<td>Slovakia</td>
<td>64</td>
<td>10</td>
<td>53</td>
<td>16</td>
<td>84</td>
</tr>
<tr>
<td>Finland</td>
<td>78</td>
<td>32</td>
<td>46</td>
<td>41</td>
<td>59</td>
</tr>
<tr>
<td>Sweden</td>
<td>101</td>
<td>64</td>
<td>36</td>
<td>64</td>
<td>36</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>123</td>
<td>92</td>
<td>31</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>Iceland</td>
<td>272</td>
<td>10</td>
<td>262</td>
<td>4</td>
<td>96</td>
</tr>
<tr>
<td>Norway</td>
<td>179</td>
<td>163</td>
<td>16</td>
<td>91</td>
<td>9</td>
</tr>
<tr>
<td>Switzerland</td>
<td>139</td>
<td>25</td>
<td>114</td>
<td>18</td>
<td>82</td>
</tr>
<tr>
<td>Macedonia</td>
<td>112</td>
<td>93</td>
<td>19</td>
<td>83</td>
<td>17</td>
</tr>
<tr>
<td>Serbia</td>
<td>93</td>
<td>27</td>
<td>66</td>
<td>29</td>
<td>71</td>
</tr>
<tr>
<td>Turkey</td>
<td>73</td>
<td>32</td>
<td>40</td>
<td>44</td>
<td>56</td>
</tr>
</tbody>
</table>

Data reveals specific conditions for different countries. In Ireland (149 m³ per inhabitant) the use of water from the public supply is still free of charge; while in Bulgaria (132 m³ per inhabitant) there are particularly high losses in the public network. Abstraction rates were also rather high in some non-member countries, notably Norway and Switzerland. In contrast, Estonia and Lithuania reported low abstraction rates, in part resulting from below-average connection rates to the public supply, while Malta and Cyprus have partially replaced groundwater by desalinated seawater.

Differences are also apparent when looking at the breakdown of water extraction between groundwater and surface water resources. Large volume of water is abstracted from surface water resources in Ireland, Greece, Spain, United Kingdom, Norway and Macedonia; while in Croatia, Italy, Lithuania, Malta, Austria, Slovenia and Slovakia, large volume of water is abstracted from groundwater resources.
3.1. **Ground Water Pumping**

Extraction of water from underground aquifers primarily requires energy for pumping. Electrical energy (kWh) is assessed based on the unit volume ($m^3$) of water that needs to be pumped during the process. An essentially linear relationship exists between the energy intensity value for the ground water pumping, the depth from which needs to be pumped and the required water pressure (Reardon D, 2010). However, total energy consumptions should also consider the efficiency of the pump and the time over which the water is pumped (D.P. Ahlfeld, 2011).

![Figure 3.2. Electricity required for pumping 1 m$^3$ of water (Martin DL, 2011)](image)

<table>
<thead>
<tr>
<th>State, Country</th>
<th>Unit Value (kWh/m$^3$)</th>
<th>Lift (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>California, USA</td>
<td>0.14 – 0.69</td>
<td>36-98</td>
<td>(GEI/Navigant, 2010)</td>
</tr>
<tr>
<td>Ontario, Canada</td>
<td>0.25 – 3.02</td>
<td>-</td>
<td>(Maas, 2010; Maas, 2009)</td>
</tr>
</tbody>
</table>

*Table 3.2. Energy Requirements for Ground Water Pumping. Values of Reference.*

Next figure shows reported energy intensity for ground water pumping at several locations in California. The figure illustrates how energy demand for ground water pumping rises with the depth from which ground water is pumped.
3.2. Surface Water Pumping

Surface water pumping refers to pumping systems such as tunnels, aqueducts, or pipelines, valves, or booster pumping stations. Its energy consumption depends on the length of the system and the elevation changes involved. As an example of a very extensive supply network, about 2.4 kW h/m$^3$ of electricity is needed to pump water from Shasta Lake in Northern California through the Central Valley in 16 km long tunnels and over the Tehachapi mountain range (600 m lift) to the Metropolitan Water District, which provides water to Los Angeles, Orange, San Diego, Riverside, San Bernardino, and Ventura counties in Southern California (Cohen, 2007), (Dale, 2004). Table below shows different examples of energy requirements for water supply systems.

<table>
<thead>
<tr>
<th>Location</th>
<th>Length, Lift (km); (m)</th>
<th>Energy (kWh/m$^3$)</th>
<th>Unit Value (kW h/m$^3$ km)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Branch Aqueduct, CA (USA)</td>
<td>(502);(-)</td>
<td>2.07</td>
<td>0.004</td>
<td>(GEI/Navigant, 2010)</td>
</tr>
<tr>
<td>Coastal Branch Aqueduct, CA (USA)</td>
<td>(457);(-)</td>
<td>2.31</td>
<td>0.005</td>
<td>(Dale, 2004) and (Anderson, 2006)</td>
</tr>
<tr>
<td>Transfer From Colorado River to Los Angeles, CA</td>
<td>(389);(-)</td>
<td>1.6</td>
<td>0.004</td>
<td>(Wilkinson, 2000)</td>
</tr>
<tr>
<td>Shoalhaven River, Australia</td>
<td>(-); (600)</td>
<td>2.4</td>
<td></td>
<td>(Anderson, 2006)</td>
</tr>
<tr>
<td>Water Pipe, Australia</td>
<td>(450);(-)</td>
<td>3.3</td>
<td>0.007</td>
<td>(Stokes J., 2009) and (Scott C., 2009)</td>
</tr>
<tr>
<td>SSDP to PIWSS, Australia $^1$</td>
<td>(116);(-)</td>
<td>0.21</td>
<td>0.002</td>
<td>(Scott C., 2009) and (AG-DSEWPC, 2010)</td>
</tr>
<tr>
<td>PSDP to PIWSS, Australia $^2$</td>
<td>11.2</td>
<td>0.055</td>
<td>0.005</td>
<td>(Scott C., 2009), (AG-DSEWPC, 2010)</td>
</tr>
</tbody>
</table>

$^1$ Southern Seawater Desalination Plant, Perth (SSDP). $^2$ Perth Integrated water supply system (PIWSS).
As it can be observed, energy intensities significantly depend on the characteristics of the location. This specificity may be due to the grade in the pipeline systems, seepage or percolation properties of soil, solar radiation per unit area, and climatic behavior in a specific geographical region. Most of the transfers consist of a complex series of pipelines, pump and turbine stations, canals, and other water bodies interconnected to each other. Each kind of transfer has an independent contribution towards the total energy consumed. Therefore, a detailed assessment must be considered for the energy use of each mode of transfer separately.

### 3.3. Water Distribution’s Energy Consumption Calculation Method

Main energy intensity in water distribution corresponds to pumping. Pumping energy consumption depends on several factors, such as the distance, friction losses, water flow and pressure requirements, expressed according to the following mathematical expression.

\[
EC_{\text{pumping}} (kWh) = f(l, Q, p, f_l)
\]

Where:

- \( l \): distance through which the water is to be pumped
- \( f_l \): friction losses along the distance \( l \)
- \( Q \): required volume of water
- \( p \): pressure requirement at the point of use

When calculating energy consumption in pumping, three different power concepts should be considered: hydraulic, mechanical and electrical.

**Hydraulic power** (\( P_{\text{hyd}} \)) refers to the power which is transferred by the pump’s shaft to the water. Three different water pumping needs can be distinguished:

- \( \Delta H \): due to height difference.
- \( \Delta P \): to compensate pressure losses along pipes and auxiliary elements (valves, elbows, etc.) in the urban water network.

---

\[2\] Perth Sea Water Desalination Plant (PSDP).
• $P_{\text{sup}}$: for necessary water pressure at the end-use sites. Only applicable in the last pipeline section which connects with the final consumer.

**Mechanical power ($P_{\text{mec}}$)** refers to the power transferred from the motor to the shaft of the pump. It depends on the efficiency of the pump ($\eta_{\text{mec}}$=mechanical efficiency).

And finally, **Supply power ($P_{\text{ener}}$)** refers to the power transferred from the energy source (electricity grid or fuel) to the motor of the pump. It depends on the efficiency of the motor ($\eta_{\text{ener}}$ = motor efficiency).

According to previous introduced concepts, **energy consumption** in a pipeline section “$I$” of the water distribution network may be defined as follows:

$$E_{\text{EN}_I} = (\Delta H_i + \Delta P_i + P_{\text{sup}}_i) \cdot \rho_{\text{water}} \cdot g \cdot \frac{1}{3600} \cdot \frac{1}{1000} \cdot \frac{100}{\eta_{\text{mec}}} \cdot \frac{100}{\eta_{\text{ener}}}$$  \hspace{1cm} \text{Equation 3.1}

Where:

$i$ = pipeline section which connects two points

$E_{\text{EN}_i}$ = Energy consumed in pumping $i$ (kWh/m³)

$\Delta H_i$ = Height difference (mwc)

$\Delta P_i$ = Pressure losses due to friction (mwc)

$P_{\text{sup}}_i$ = Supplied Pressure need for the final consumer (mwc).

$\rho_{\text{water}}$ = Density of water \(1000 \text{ kg/m}^3\)

$g$ = Gravity \(9.81 \text{ m/s}^2\)

$\eta_{\text{mec}}$ = Average mechanical efficiency

$\eta_{\text{ener}}$ = fuel or electrical average efficiency of the motor

### 3.3.1. Height difference - $\Delta H$

Height difference, also named geometric height difference is defined as the difference in level between two points of the urban water network (for example between the supply points and the distribution tank).

### 3.3.2. Friction pressure losses - $\Delta P$
Pressure losses along a pipe due to friction can be calculated as:

\[
\Delta P = f \cdot \frac{L}{D/1000} \cdot \frac{v^2}{2 \cdot 9.81 \cdot (1 + \frac{\%LOC}{100})}
\]

Equation 3.2

Where:
- \( f \) = Darcy – Weisbach friction factor
- \( D \) = Internal diameter of the pipe (mm)
- \( L \) = Pipe length (m)
- \( v \) = average water velocity (m/s)
- \( \%LOC \) = percentage of the friction losses (%)

The friction factor \( f \) is estimated with the Colebrook White’s equation for turbulent flow:

\[
\frac{1}{\sqrt{f}} = -2 \log_{10} \left( \frac{k / D}{3.7 \cdot 1000} + \frac{2.51}{R_e \sqrt{f}} \right)
\]

Equation 3.3

Where:
- \( R_e = \frac{\nu}{\theta \cdot \frac{D}{1000}} = Reynolds\ Number \)
  - \( \theta = Kinematic\ water\ viscosity (10^{-6}\ m^2/s) \)
  - \( k = roughness\ of\ duct,\ pipe\ or\ tube\ surface\ (mm) \)

3.3.3. Supplied pressure - \( P_{SUP} \)

Supplied pressure is the available pressure at the end-use sites. Recommended values are approximately 300 kPa or 30.6 mwc. (meter water column).

3.3.4. Total energy consumption in water distribution

Total energy consumption for water pumping in the distribution network is calculated as the sum of energy consumed in height and pressure losses of all pipeline sections of the system:
\[ E_{\text{ENETotal}} = \sum_i (\Delta H_i + \Delta P_i + P_{\text{sup}}_i) \cdot \rho_{\text{water}} \cdot g \cdot \frac{1}{3600} \cdot \frac{1}{1000} \cdot \frac{100}{\eta_{\text{mec}}} \cdot \frac{100}{\eta_{\text{ener}}} \]  

Equation 3.4

Where:

\[ i = \text{pipeline section which connects two points} \]

\[ E_{\text{ENETotal}} = \text{Total Energy consumed due pumping } i \text{ (kWh/m}^3\text{)} \]

\[ \Delta H_i = \text{Height difference (mwc)} \]

\[ \Delta P_i = \text{Pressure losses due to friction (mwc)} \]

\[ P_{\text{sup}}_i = \text{Supplied Pressure need for the final consumer (mwc)} \]

\[ \rho_{\text{water}} = \text{Density of water (1000 kg/m}^3\text{)} \]

\[ g = \text{Gravity (9.81 m/s}^2\text{)} \]

\[ \eta_{\text{mec}} = \text{Average mechanical efficiency} \]

\[ \eta_{\text{ener}} = \text{fuel or electrical average efficiency of the motor} \]

Total emissions due to water pumping are calculated as follows:

\[ E_{\text{MITotal}} = \sum_i E_{\text{ENETotal}} \cdot E_{\text{FI}} \]  

Equation 3.5

Where:

\[ E_{\text{MITotal}} = \text{Total emissions due to pumping (kg CO}_2\text{e/m}^3\text{)} \]

\[ E_{\text{ENETotal}} = \text{Energy consumed in pumping } i \text{ (kWh/m}^3\text{)} \]

\[ E_{\text{FI}} = \text{Emission factor for fuel or electricity (kg CO}_2\text{e/kWh)} \]
4. **Water Treatment**

Seven percent of worldwide electricity is consumed for the production and distribution of drinking water and for treating waste water (Young, 2010). Before supplying water to consumers, it must be treated to appropriate physical and chemical quality. Generally, potable water at the point of supply should have a turbidity less than or equal to 5NTU and zero fecal coliforms per 100mL of water as per WHO guidelines, UK Regulations, European Commission directives, USEPA regulations, or and Bureau of Indian Standards guidelines [(Murty BS, 2011), (Twort AC, 2001)].

4.1. **Water Treatment at the Source**

4.1.1. Surface water treatment

Several surface water treatment datasets have been collected, identifying daily electricity consumption for various treatment processes, as shown in table below. Surface plant sized range from 3785 m$^3$/day to 378500 m$^3$/day.

<table>
<thead>
<tr>
<th>Item/Plant Production</th>
<th>Treatment Plant Size (m$^3$/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3785</td>
</tr>
<tr>
<td></td>
<td>Electricity consumption (kWh/day)</td>
</tr>
<tr>
<td>Rapid Mixing</td>
<td>41</td>
</tr>
<tr>
<td>Flocculation</td>
<td>10</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>14</td>
</tr>
<tr>
<td>Alum Feed System</td>
<td>9</td>
</tr>
<tr>
<td>Polymer Feed System</td>
<td>47</td>
</tr>
<tr>
<td>Lime Feed System</td>
<td>9</td>
</tr>
<tr>
<td>Filter Surface Wash Pumps</td>
<td>8</td>
</tr>
<tr>
<td>Backwash Water Pumps</td>
<td>13</td>
</tr>
<tr>
<td>Residuals Pumping</td>
<td>4</td>
</tr>
<tr>
<td>Thickened Solids Pumping</td>
<td>N/A</td>
</tr>
<tr>
<td>Chlorination*</td>
<td>2</td>
</tr>
<tr>
<td>General UV Irradiation$^[1]*$</td>
<td>114</td>
</tr>
<tr>
<td>Ozone$^[1]*$</td>
<td>341</td>
</tr>
</tbody>
</table>

*Disinfection processes: Chlorination is the widest disinfection treatment, UV Irradiation and Ozonation are usually need Chlorination as a residual disinfection process.

Table 4.1. Electricity requirements for processes used in surface water treatment plants (Burton, 1996), (Gleik, 2009)$^[1]$  

Unit electricity consumption in kWh/m$^3$ for different types of treatment within surface water treatment plants are exposed above. Processes may be organized in two types: **Basic DWTPs**, which include just flocculation, sedimentation and chlorination processes-, and **complete DWTPs**, which
include all the processes shown in the table plus different disinfection processes (Chlorination, UV Irradiation or Ozonation).

<table>
<thead>
<tr>
<th>Treatment Plant Size (m$^3$/day)</th>
<th>3785</th>
<th>18925</th>
<th>37850</th>
<th>75700</th>
<th>189250</th>
<th>378500</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electricity consumption for Basic Treatment (kWh/day)</td>
<td>26</td>
<td>97</td>
<td>180</td>
<td>358</td>
<td>894</td>
<td>1788</td>
<td></td>
</tr>
<tr>
<td>Total Electricity consumption for Basic Treatment (kWh/m$^3$)</td>
<td>0.0069</td>
<td>0.0051</td>
<td>0.0048</td>
<td>0.0047</td>
<td>0.0047</td>
<td>0.0047</td>
<td>0.0052</td>
</tr>
<tr>
<td>Total Electricity consumption for Complete Treatment with Chlorination (kWh/day)</td>
<td>157</td>
<td>463</td>
<td>797</td>
<td>1656</td>
<td>4084</td>
<td>8082</td>
<td></td>
</tr>
<tr>
<td>Total Electricity consumption for Complete Treatment with Chlorination (kWh/m$^3$)</td>
<td>0.041</td>
<td>0.024</td>
<td>0.021</td>
<td>0.022</td>
<td>0.022</td>
<td>0.021</td>
<td>0.0253</td>
</tr>
<tr>
<td>Total Electricity consumption for Complete Treatment with UV Radiation (kWh/day)</td>
<td>271</td>
<td>1031</td>
<td>1933</td>
<td>3927</td>
<td>9762</td>
<td>19437</td>
<td></td>
</tr>
<tr>
<td>Total Electricity consumption for Complete Treatment with UV Radiation (kWh/m$^3$)</td>
<td>0.071</td>
<td>0.054</td>
<td>0.051</td>
<td>0.052</td>
<td>0.052</td>
<td>0.051</td>
<td>0.0553</td>
</tr>
<tr>
<td>Total Electricity consumption for Complete Treatment with Ozonation (kWh/day)</td>
<td>498</td>
<td>2166</td>
<td>4204</td>
<td>8469</td>
<td>21117</td>
<td>42147</td>
<td></td>
</tr>
<tr>
<td>Total Electricity consumption for Complete Treatment with Ozonation (kWh/m$^3$)</td>
<td>0.131</td>
<td>0.114</td>
<td>0.111</td>
<td>0.112</td>
<td>0.112</td>
<td>0.111</td>
<td>0.1153</td>
</tr>
</tbody>
</table>

*Table 4.2. Electricity requirements in different types of surface water treatment plants*

As a result, it was concluded that variation in unit electricity consumption with size was not very significant.

4.1.2. Ground water treatment

The process sequence for groundwater treatment is usually less severe than for surface water (EPRI, 2002). Therefore, it is much less energy intensive.

Ground water pumped from subterranean aquifers may be discolored and may contain dissolved gases, inorganic and organic chemicals, or in some cases microorganisms. Basic disinfection of ground water might be carried out with the help of technologies such as chlorination, ozonation or ultraviolet irradiation. A ground water treatment plant may have a pumping system, a storage tank, a disinfection tank, and a booster distribution pump. Aeration to remove dissolved gases, oxidation and filtration to remove iron or manganese, or softening to remove calcium and magnesium ions may be applied as required. (Plappally A.K., 2012)

Potable water is chlorinated to eliminate microbial contamination. Chlorination is usually accomplished by injection of chlorine gas into water or by the addition of salts such as calcium and
sodium hypochlorite, containing around 70% chlorine, which form hypochlorite ions on contact with water (Twort AC, 2001).

Studies in energy consumption in surface water treatment plants show that the raw water pumping intensity (e.g., from river to treatment plant 0.02–0.05 kW h/m$^3$) is minimal when compared to values seen previously for ground water pumping (WEF, 2010).

![Energy consumption of unit processes in surface water treatment plants in United States (WEF, 2010)](image)

Energy consumption for water treatment in several countries is showed in the table below. As it can be observed, Spain is seen to have highest upper limit energy consumption for water treatment, since it uses reverse osmosis desalination to treat some water (Muñoz I., 2010) and these processes can be very energy intensive. Also, Canada has a high energy intensity due to the use of high energy membrane processes such as ultrafiltration in use and smaller plant sizes (<500,000 m$^3$/d) (Maas, 2009).

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy Needs</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>0.01–0.2</td>
<td>(Cammerman, 2009)</td>
</tr>
<tr>
<td>Taiwan</td>
<td>0.16–0.25</td>
<td>(Cheng, 2002)</td>
</tr>
<tr>
<td>USA</td>
<td>0.184–0.47</td>
<td>(WEF, 2010)</td>
</tr>
<tr>
<td>Canada</td>
<td>0.38–1.44</td>
<td>(Maas, 2010)</td>
</tr>
<tr>
<td>Spain</td>
<td>0.11–1.5</td>
<td>(Muñoz I., 2010)</td>
</tr>
<tr>
<td>New Zealand</td>
<td>0.15–0.44</td>
<td>(Kneppers B, 2009)</td>
</tr>
</tbody>
</table>

*Table 4.3. Conventional water treatment energy consumption ranges in several countries (kWh/m$^3$)*

Considering the plant size, next table provides unit electricity consumption for three different disinfecting processes which can be used in groundwater treatment plants, ranging from 3785 m$^3$/day to 75700 m$^3$/day in size:
4.1.3. Desalination

In arid and water scarce areas, desalination technologies have become a viable source of water. Desalination is employed to remove high concentrations of minerals and salts from seawater as well as in treatment or recycling of brackish water.

The minimum energy required to desalinate water is proportional to the salinity of the raw water, but the energy required in practice also depends upon the technology employed. The energy consumed in membrane processes such as reverse osmosis, nanofiltration, and electrodialysis varies with the salinity of the water whereas the energy required in thermal distillation processes is independent of the salinity of the source water. The minimum energy consumption in reverse osmosis membrane processes is determined by the need to pressurize the inlet water stream above its corresponding osmotic pressure (Elimelech M., 2011) and (Singh, 2011).

Depending on the desalination technology used (Multi-Stage Fash evaporation, Multiple-Effect Distillation, Multiple-effect distillation with thermal vapour compression, evaporation with Mechanical Vapour Compression, or Reverse Osmosis) and the plant capacity, energy intensity differs.

![Table 4.4. Electricity consumption for different disinfecting processes and plant sizes (kWh/m³)](data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAIgAAAAWCAYAAAApX9Z7AAAgAElEQVR42UQ1dXQWgUDwAIAwEAgAAAAAABAQCBgAAAAABJRU5ErkJggg==)

**Table 4.4. Electricity consumption for different disinfecting processes and plant sizes (kWh/m³)**

<table>
<thead>
<tr>
<th>Treatment Plant Size (m³/day)</th>
<th>Electricity consumption (kWh/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3785</td>
<td>79 51 93 186</td>
</tr>
<tr>
<td>18925</td>
<td>79 51 93 186</td>
</tr>
<tr>
<td>37850</td>
<td>79 51 93 186</td>
</tr>
<tr>
<td>75700</td>
<td>79 51 93 186</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processes</th>
<th>Chlorination</th>
<th>General UV Irradiation</th>
<th>Ozone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9</td>
<td>76</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>379</td>
<td>568</td>
</tr>
<tr>
<td></td>
<td>93</td>
<td>757</td>
<td>1136</td>
</tr>
<tr>
<td></td>
<td>186</td>
<td>1514</td>
<td>2271</td>
</tr>
</tbody>
</table>

Table 4.5. Energy consumption in Desalination Technologies (kWh/m³). (IDA, 2012)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Plant Capacity (m³/day)</th>
<th>Thermal Energy (kWh/m³)</th>
<th>Electrical Energy (kWh/m³)</th>
<th>Operation Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSF</td>
<td>4000-450000</td>
<td>55-220</td>
<td>4-6</td>
<td>90-112</td>
</tr>
<tr>
<td>MED</td>
<td>100-56000</td>
<td>40-220</td>
<td>1.5-2.5</td>
<td>50-70</td>
</tr>
<tr>
<td>MVC</td>
<td>5-17000</td>
<td>-</td>
<td>6-12</td>
<td>50-70</td>
</tr>
<tr>
<td>RO</td>
<td>0.01-360000</td>
<td>-</td>
<td>2.8-12</td>
<td>&lt;40</td>
</tr>
</tbody>
</table>
4.2. Water Treatment’s Energy Consumption Calculation Method

This section includes the calculation method followed for estimating the annual energy consumption (kWh/year) and emissions (kgCO₂e/year) for the three water treatment processes presented in the previous section:

- Surface water treatment plants
- Groundwater treatment plants
- Desalinization plants

When a DWTP capacity is expressed in m³/day, average unit energy consumptions in kWh/m³ is obtained from its corresponding table (surface water treatment plants, ground water treatment plants and Desalinization Plants).

In this case, annual energy consumption in a DWTP can be easily calculated as follows:

\[
EC_{DWTP_i} \left( \frac{kWh}{year} \right) = Capacity_{DWTP_i} \left( \frac{m^3}{day} \right) \cdot UEC_{DWTP_i} \left( \frac{kWh}{m^3} \right) \cdot \frac{365 \, days}{1 \, year}
\]

Equation 4.1

Where:

\( i = \) type of treatment plant (surface, groundwater or desalinization plant)

\( EC_{DWTP_i} = \) annual energy consumption in the water treatment plant \( i \) \( \left( \frac{kWh}{year} \right) \)

\( Capacity_{DWTP_i} = \) Capacity of the drinking water treatment plant \( \left( \frac{m^3}{day} \right) \)

\( UEC_{DWTP_i} = \) Unit energy consumption in the water treatment plant \( i \) \( \left( \frac{kWh}{m^3} \right) \)

Annual energy consumption in water treatment is calculated as:

\[
EC_{DWP} \left( \frac{kWh}{year} \right) = \sum \left( EC_{DWTP_i} \left( \frac{kWh}{year} \right) \cdot US_i(\%) \right)
\]

Equation 4.2

Where:

\( i = \) type of treatment plant (surface, groundwater or desalinization plant)
Finally, annual emissions from a DWTP Plant are calculated as shown below:

\[
E_{\text{DWTP}} (\text{kg CO}_2\text{e year}) = EC_{\text{DWP}} (\text{kWh year}) \cdot EF_{\text{elec. coun.}} (\text{kg CO}_2\text{e kWh})
\]

Equation 4.3

Where:

\[
E_{\text{DWTP}} = \text{annual energy emissions in the drinking water production (kg CO}_2\text{e year)}
\]

\[
EC_{\text{DWP}} = \text{annual energy consumption in the water production (kWh year)}
\]

\[
EF_{\text{elec. coun.}} = \text{Emission factor for electricity production of a country or region (kg CO}_2\text{e kWh)}
\]
5. Wastewater Treatment

Water used in the urban cycle gets polluted with liquid and solid waste and it is treated with primary, secondary and sometimes tertiary treatment stages. Primary treatment processes include waste collection, screening, chemical treatment, grit removal and sedimentation. Secondary treatment processes include aeration, stabilization, suspended growth or fixed film processes, clarification, and membrane bioreactor processes. Secondary processes only remove 20–30% of nitrogen from the waste waters. Higher nitrogen and phosphorus removal can be met by use of tertiary processes such as nitrification–denitrification. These processes can consume substantial amounts of energy. The energy consumed by these processes depends on size of the plant, the location of the treatment plant, the population served, the type of impurity, the type of treatment process, the end users of water in the area, quality of water the treatment plants receive, quality of treatment required for water discharge, economic status of the waste water treatment plant, and the experience of the plant managers [Hammer MJ, 2008]. [Murty BS, 2011]. [Twort AC, 2001]. [WEF, 2010]]. The type of impurity to be removed is the major parameter that drives energy consumption in waste water or water treatment.

5.1. Primary Treatment

Primary treatment includes screening, size reduction and inorganic suspended solids removal process. These are low energy intensity processes. Primary sludge pumping is the most energy consuming primary treatment process. For example, in USA the average energy consumption in raw sewage collection and pumping is 0.04 kWh/m³, and concretely California shows an estimated energy consumption in influent waste water pumping and collection in the range from 0.003 to 0.04 kWh/m³ [CEC, 2006]. [GEI/Navigant, 2009]]. In New Zealand waste water pumping ranges from 0.04 to 0.19 kWh/m³, while Canada estimates its energy consumption from 0.02 to 0.1 kWh/m³ [Kneppers B, 2009]. [Maas, 2009]]. The grit removal processes basically rely on grit collection in an inverted conical vessel with a grit discharge. The inorganic grit targeted at this stage has an approximate specific gravity of 2.65 [Murty BS, 2011]. Energy is consumed to drive the grit pumps, which conveys grit to a dumping place. Once the grit is removed, wastewater is sent to the primary sedimentation tank. Roughly 60% of suspended organic solids as well as 30% BOD (biochemical oxygen demand) is removed in the primary sedimentation tank [Murty BS, 2011]. Energy use for the sedimentation is low, around 0.008-0.01 kWh/m³ [Tassou, 1988]. As an indication, it is known that total energy consumed for this primary treatment in Australia ranged from 0.01–0.37 kWh/m³ [Kenway SJ, 2008].

Chemicals are also sometimes used to increase the biological oxygen demand as well as to reduce the organic load in the sludge. Rapid mixing, chemical pumping, polymer pumping, chemical transfer pumping are some of the pumping processes when chemical addition is performed. Poor primary treatment design and operation could affect the overall energy footprint of the waste treatment plant.

5.2. Secondary Treatment

Waste water with remaining colloidal organic impurities such as proteins and dissolved organic matter, such as carbohydrates, enters secondary treatment. Biological treatment is predominant in this stage of waste water treatment. This induces the need for enough oxygen to run the processes. Mechanical
or surface (Used in continuously stirred tank) and diffused (used in plug flow) aeration systems are used for this purpose. Aerators also help proper mixing of the waste sludge apart from providing more oxygen. Aeration blowers consume half the energy consumed by diffused aeration secondary treatment systems (WEF, 2010). Data provided from Wisconsin denotes that energy efficient air blower aeration devices consume 0.026 – 0.04 kWh/m³ (Toffey, 2010). The average consumption of mixing and pumping action at this stage for a 1.000 m³ sewage plant is in the range of 0.012 – 0.033 kWh/m³ (Tassou, 1988). Organic impurities are acted upon by heterotrophic microorganisms present in wastewater within aerator systems in the presence of oxygen. For conventional aeration processes the oxygen concentration is between 0.5 and 1.0 mg/L while in extended aeration 1.5 and 2.0 mg/L of oxygen is necessary (WEF, 2010).

There are many available aeration technologies and devices in the market, including static tube diffused aerators and fine bubble flexible diffusers (WEF, 2010). Fine bubble flexible diffusers consume only half the energy consumed by static tube diffused aerators (WEF, 2010). Another type of diffuser is the porous diffuser, to provide fine pore aeration. Fine pore diffusers produced oxygen at the rate 1.2 - 2 kg/kWh and consumed approximately 0.037 kWh to aerate a m³ of water [ (Murty BS, 2011). (Toffey, 2010)]. An energy intensity of 0.055 kWh/m³ was measured in ultrafine porous diffusers by Toffey (Toffey, 2010). Surface aerators in India produced 1.2 – 2.4 kg of oxygen per kWh of electricity consumption (Murty BS, 2011).

Oxidation results in the breakdown of organic material to carbon dioxide and water, and further produces flocculating microbe biomass. Once the microbial biomass reaches the endogenous phase, it starts producing exocellular polymers which have binding properties (Murty BS, 2011). Once this action takes place, the residual wastewater with the flocculation biomass is sent to a secondary sedimentation tank. Dome part of the flocculating biomass settles under gravity and is removed from the wastewater system here. About 30% of this removed biomass is recycled back to the aerator while the rest is sent to the sludge treatment system (Murty BS, 2011). This recirculation is performed to maintain the desired biomass concentration in the aerator. Recirculation pumping in activated sludge processes was reported to consume an average of 0.011 of energy (Tassou, 1988). Digestion is the term used to define these processes of converting the organic solids in the sludge treatment tanks to more inert forms suitable for disposal. Data from Australia shows that the energy consumed by aerobic digestion process in a biological nutrient removal sewage treatment plant was reported to be approximately 0.5 kWh/m³ (Radcliffe, 2004).

In China, aeration systems like wetlands and land treatment had an average energy consumption of 0.253 kWh/m³ while aeration processes in the UK were reported to consume an average of 0.13 kWh/m³ of electrical energy [ (Tassou, 1988). (Yang L, 2010)].

Additional aeration processes include oxidation ditches, which help to improve the oxygen content of wastewater. Oxygen content helps the removal of nitrates from the wastewaters (WEF, 2010). High oxygen demand and long residence time increases energy intensity of oxidation ditches more than activated sludge processes (Mizuta K, 2010). Table below shows a relation of different energy intensity processes in Australia, China and Japan. It can be observed that aeration or oxidation ditch processes consumed more energy that activated sludge processes [ (Yang L, 2010). (Mizuta K, 2010)]. Activated sludge processes involve suspensions of active microbial cultures in a reactor, where air or
Oxygen can be introduced to sustain microbial activity. These systems are suspended growth systems where microbial biofilm surfaces help in breaking down the organic and inorganic constituents of the wastewater flooded on these surfaces. Processes such as return sludge pumping and thickening are included in activated sludge wastewater treatment plants. The least energy intensity aeration systems are lagoons and trickling filter (fixed film) process.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Australia</th>
<th>China</th>
<th>USA</th>
<th>Japan</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagoons</td>
<td>0.253 (avg)</td>
<td>0.09 - 0.29</td>
<td></td>
<td></td>
<td>(Yang L, 2010). (Quantum Consulting, 2001)</td>
</tr>
<tr>
<td>Activated sludge</td>
<td>0.1 (avg)</td>
<td>0.269 (avg)</td>
<td>0.33 – 0.6</td>
<td>0.30 -1.89</td>
<td>(WEF, 2010). (Yang L, 2010). (Mizuta K, 2010).</td>
</tr>
<tr>
<td>Oxidation ditch</td>
<td>0.5 – 1.0</td>
<td>0.302</td>
<td></td>
<td>0.43 – 2.07</td>
<td>(Yang L, 2010). (Mizuta K, 2010).</td>
</tr>
<tr>
<td>Membrane bio-reactor</td>
<td>0.10 – 0.82</td>
<td>0.33 (avg)</td>
<td>0.8 – 0.9;</td>
<td>0.49 – 1.5</td>
<td>(WEF, 2010). (Yang L, 2010). (Lesjean B, 2011).</td>
</tr>
<tr>
<td>Trickling filter</td>
<td></td>
<td>0.18 – 0.42</td>
<td></td>
<td></td>
<td>(Quantum Consulting, 2001). (EPA, 2008)).</td>
</tr>
</tbody>
</table>

Table 5.1. Energy intensity of secondary waste water treatment (kWh/m³)

Anaerobic digestion usually takes place in three steps. First, hydrolysis of organic mass and proteins occur in the microbial media. Enzymes produced by anaerobic microbes break down these organic and protein macromolecules into small digestible forms. Second, these molecules are decomposed into small fatty acids. This decomposition is performed by anaerobic bacteria. Finally, methane producing bacteria digest these fatty acids, resulting in the formation of methane, ammonia, hydrogen sulfide, and carbon dioxide in gaseous form (Metcalf L, 1979). This gas has a fuel value of approximately 6.2 kWh/m³ (Stillwell AS, 2010). Anaerobic digestion has the capacity to deliver gas at the rate 35 m³/d per person (Stillwell AS, 2010). The case of the new biological wastewater purification facility in Singapore produces methane enough to supply energy equivalent to its consumption, approximately 0.25 kWh/m³ (Greencarcongress, 2011). Digested sludge can also be valorized as soil fertilizer for agricultural farms (Murty BS, 2011).

Membrane bioreactors are designed to operate at comparatively high suspended solids concentration compared to activated sludge processes. Advantages over the activated sludge are comparatively higher loading rate, short detention time, operation at low dissolved oxygen conditions, better effluent quality and no requirement for clarifiers (Davis, 2010). (Murty BS, 2011). Membrane bioreactors help to separate the solids from the mixed digested sludge. It implies to overcome the transmembrane pressure (7-65 kPa) across these micro or ultrafiltration devices to filter the waste activated sludge, which adds energy requirements.

Finally, the effluents from the activated sludge or trickling filter or membrane filters are disinfected as required. Chlorination as well as ultraviolet disinfection methods are practiced. Energy needs for chlorination are similar to those for drinking water disinfection processes used in the water treatment
stage, while UV disinfection consumes from 0.066 to 0.021 kWh/m³ depending on the disinfection appliance used.

5.3. TERTIARY TREATMENT

The energy consumed by waste treatment plants varies depending on the final number of treatments applied. Sometimes secondary processes are unable to achieve complete removal of ammonia and a tertiary treatment is necessary. Nitrate is converted to nitrogen in an aerobic process with addition of methanol or anaerobic process by addition of ammonia (Murty BS, 2011). Advanced water treatment with nitrification consumed energy in the range of 0.40–0.50 kW h/m³ (EPA, 2008).

The energy intensity of anaerobic digestion is around 0.28 kW h per cubic meter of wastewater (Crawford, 2009). In Japan, advanced wastewater treatment is highly energy intensive with an energy consumption range of 0.39–3.74 kW h/m³ (Mizuta K, 2010). The large energy consumption values in Japan are related to the small size of the decentralized wastewater treatment plants (Mizuta K, 2010).

Lagoons also offer further opportunities to treat and aerate the wastewater and remove excess nitrates in tertiary water treatment before the treated wastewater or sludge is discharged to the receiving environments (ocean, rivers or ground recharge). They are low intensity processes with an energy consumption range of 0.09–0.29 kW h/m³ (Quantum Consulting, 2001).

5.4. WASTEWATER TREATMENT ENERGY CONSUMPTION CALCULATION METHOD

Annual energy consumption (kWh/year) and emissions (kgCO₂e/year) in WWT are calculated for the following four representative types of WWTPs treatments.

- Only primary treatment
- Aerated Basins (basic treatment)
- Activated Sludge with nutrients removal
- Activated Sludge without nutrients removal
- Trickling Filter
- Advanced Wastewater Treatment with Nitrification

Electricity consumption in wastewater treatments is calculated using data from the table below, which relates energy consumption with plant size. As approached in previous methods, these energy indicators will be used for the calculations. In case primary treatment applies, energy consumption coefficient of 0.01 kgCO₂/m³ should be also considered.
Advanced wastewater treatment with nitrification is considered as a tertiary treatment, with an energy consumption coefficient of 0.45 kWh/m$^3$. It corresponds to an advanced treatment, so no all plants will implement it. Thus, an average value of the different energy consumption data identified in relation to the plant size was used.

Unit energy consumption is selected using a discrete approach (kWh/m$^3$), identifying the energy consumption indicator according to the plant size. WWTP capacity may be expressed in m$^3$/day BOD$_5$ or PE (population equivalent). When capacity is expressed in BOD$_5$ or PE, then initial conversion to m$^3$/day is required. In these cases, it is necessary to identify the equivalent kgO$_2$/day and PE representative factors for the country/region under study. For example, in the case of Spain BOD$_5$ factor is 0.06 kg O$_2$/day.

To proceed with the BOD$_5$ conversion, the following mathematical expression may be used:

$$Capacity_{WWTP} (PE) = BOD_5 \left(\frac{1000 \text{ kg O}_2}{\text{day}}\right) \cdot \frac{1 \text{ PE}}{0.06 \text{ kg O}_2/\text{day}}$$  \hspace{1cm} Equation 5.1

Where:

$Capacity_{WWTP} =$ Waste water treatment plant capacity in Population Equivalent (PE)

$BOD_5 =$ five day biochemical oxygen demand $\left(\frac{1000 \text{ kg O}_2}{\text{day}}\right)$

According to Directive 91/271/EEC: 1 P.E $\rightarrow$ BOD$_5 = 60 \frac{\text{gO}_2}{\text{day}}$

Then, WWTP capacity in PE is converted to m$^3$/day as follows:

$$Capacity_{WWTP} \left(\frac{\text{m}^3}{\text{day}}\right) = Capacity_{WWTP} (PE) \cdot WW \text{ Influent} \left(\frac{\text{m}^3}{\text{PE} \cdot \text{day}}\right)$$  \hspace{1cm} Equation 5.2
Where:

\[ \text{Capacity}_{\text{WWTP}} = \text{Waste water treatment plant capacity} \left( \frac{m^3}{\text{day}} \text{ or PE} \right) \]

\[ \text{WW Influent} = \text{Waste water Influent or volume of waste water treated in a waste water treatment plant per day and PE} \left( \frac{m^3}{\text{PE}. \text{day}} \right) \]

Once WWTP capacity is expressed as \( m^3/\text{day} \), unit energy consumption in kWh/m\(^3\) can be selected from table above. Subsequent, annual energy consumption in a WWTP can be easily calculated as follows:

\[ EC_{\text{WWTP}} \left( \frac{kWh}{\text{year}} \right) = \text{Capacity}_{\text{WWTP}} \left( \frac{m^3}{\text{day}} \right) \cdot UEC_{\text{WWTP}} \left( \frac{kWh}{m^3} \right) \cdot \frac{365 \text{ days}}{1 \text{ year}} \]

Equation 5.3

Where:

\[ EC_{\text{WWTP}} = \text{annual energy consumption in a wastewater treatment plant} \left( \frac{kWh}{\text{year}} \right) \]

\[ \text{Capacity}_{\text{WWTP}} = \text{Wastewater treatment plant capacity} \left( \frac{m^3}{\text{day}} \right) \]

\[ UEC_{\text{WWTP}} = \text{Unit energy consumption in the wastewater treatment plant} \left( \frac{kWh}{m^3} \right) \]

Finally, annual emissions from a WWTP are calculated as shown below:

\[ E_{\text{WWTP}} \left( \frac{kg \ CO_2e}{\text{year}} \right) = EC_{\text{WWTP}} \left( \frac{kWh}{\text{year}} \right) \cdot EF_{\text{elec.count}} \left( \frac{kg \ CO_2e}{kWh} \right) \]

Equation 5.4

Where:

\[ E_{\text{WWTP}} = \text{annual energy emissions in a wastewater treatment plant} \left( \frac{kg \ CO_2e}{\text{year}} \right) \]

\[ EC_{\text{WWTP}} = \text{annual energy consumption in a wastewater treatment plant} \left( \frac{kWh}{\text{year}} \right) \]

\[ EF_{\text{elec.count}} = \text{Emission factor for electricity production of a country or region} \left( \frac{kg \ CO_2e}{kWh} \right) \]
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6. BUILDING INSULATION

6.1. ENERGY CONSUMPTION IN BUILDINGS

Buildings consume about 40% of total final energy requirements in Europe in 2010. It is the largest end use sector, followed by transport (32%), industry (24%) and agriculture (2%). Thus, building sector is one of the key energy consumers in Europe, where energy use has increased a lot over the past 20 years. A wide array of measures has been adopted at EU level and implemented across individual Member States to actively promote the better energy performance of buildings (ADEME, 2012). In 2002, the Directive on the Energy Performance of Buildings (EPBD) was adopted and recast in 2010 with more ambitious goals. More recently in the Energy Efficiency Plan 2011, the European Commission states that the greatest energy saving potential lies in buildings.

Average annual energy consumption was around 220 kWh/m² in 2009, with a large gap between residential (around 200 kWh/m²) and non-residential buildings (around 300 kWh/m²) (ADEME, 2012).

The Buildings Performance Institute Europe (BPIE) undertook a large survey of the European building stock in 2010. The study (Buildings Performance Institute of Europe, 2011) estimated that there are 25 billion m² of useful floor space in the EU27, where Switzerland and Norway are roughly equivalent to the land area of Belgium (30 528 km²).

Natural gas is the dominant source of energy for households in the EU with 39 % of the market, up from 29 % in 1990. Electricity ranks second and its share is also increasing rapidly (from 19% in 1990 to 25% in 2009). Oil is slowly being phased out at EU average (from 22% in 1990 to 15% in 2009), but remains significant in island countries (ADEME, 2012).

![Figure 6.1. Household energy consumption by energy source in EU.](image-url)
Since energy consumption in buildings relies mainly on non-renewable resources it is important to find ways to save energy as a first step to mitigate environmental impacts and to preserve fuel resources.

In 2009, European households were responsible for 75% of the total final energy use in buildings. A quarter of the European building stock consists of non-residential buildings, around 50% of which are offices, wholesale and retail buildings.

![Figure 6.2. Energy consumption by building categories in Europe.](image)

At EU level, space heating and cooling is the predominant end-use (67%) but its share is slightly declining since 2000. Water heating ranks second and have a stable share (13%). Electrical appliances and lighting absorb an increasing share of the consumption (+4 points).

These trends are the result of important efforts invested in energy efficiency improvements for space heating, building regulations and the diffusion of more efficient heating appliances. Besides, new electrical appliances have become more popular in its use. (ADEME, 2012).

European countries households’ energy use are showed in the next figure.

![Figure 6.3. Household energy consumption by end-use for EU-countries (ADEME, 2012)](image)
Today, many of the existing European buildings (more than 40%) are built before 1960s, where there were only few or no requirements for energy efficiency. Besides, only a small part of these have implemented major energy retrofits, meaning that, these have low insulation levels and their systems are old and inefficient. In fact, the oldest part of the building stock contributes greatly to the high energy consumption in the building sector (Buildings Performance Institute of Europe, 2011).

During the last years, several improvements have been achieved in heating systems. However, there is still a large saving potential associated with residential buildings that has not been exploited. New technologies are easily implemented in new buildings, but the challenge is mostly linked to existing stock which includes the majority of European buildings (Buildings Performance Institute of Europe, 2011). This is where greenroof may be helpful, since it is easy to install in existing buildings and provides extra ceiling insulation.

6.2. HEAT TRANSFER IN BUILDING ELEMENT

Heat transfer in buildings is analyzed by subdividing the structure into different enclosures or elements (facade walls, openings, floors and roofs), to calculate separately heat loss.

This type of calculation is usually based on a one-dimensional model, which assumes that the elements are thermally homogeneous and are composed of a number of layers in parallel to the heat flow, as shown in the next figure.

Heat transfer is defined as the Heat Transfer Coefficient \( U \), considered in a simplified, steady state. This value gives the heat loss through each building element per unit surface area and temperature difference of the considered element (W/m²·K).

U-value for each element of the building is calculated by the following general equation:

\[
U \left( \frac{W}{m^2 \cdot K} \right) = \frac{1}{R_{SI} + R_{SO} + R_1 + R_2 + \cdots + R_n}
\]

Equation 6.1
Where:

\[ R_{SI} \left( \frac{m^2 \cdot K}{W} \right) = \text{thermal resistance of internal surface (outside air)} \]

\[ R_{SO} \left( \frac{m^2 \cdot K}{W} \right) = \text{thermal resistance of outside surface (indoor air)} \]

\[ R_i \left( \frac{m^2 \cdot K}{W} \right) = \text{thermal resistance of layers which compounds the element} \]

**Thermal resistance, \( R_i \)** of a thermally homogeneous layer is defined as follows:

\[
R_i \left( \frac{m^2 \cdot K}{W} \right) = \frac{t}{\lambda} 
\]

Where:

\[ t = \text{layer thickness (m)} \]

\[ \lambda = \text{thermal conductivity of the material which compounds the layer} \left( \frac{W}{m \cdot K} \right) \]

The prevalent materials in a roof and their thermal conductivities are the ones showed in the table below. The values are for normal temperature and should be regarded as average values for the type of material specified:

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity ( W/(m \cdot K) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>XPS (Extruded Polystyrene) Insulation</td>
<td>0.04–0.14*3</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.33–0.52*3</td>
</tr>
<tr>
<td>Air</td>
<td>0.025*</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.1–1.8*</td>
</tr>
</tbody>
</table>

* Values depend on density, generally increasing with increasing density.

(Kaye and Laby, 2013)

**Table 6.1. Thermal conductivities of common materials found in roofs**

The heat losses through an element of the building are characterized by the following equations:

\[
Q \left( W \right) = U \cdot A \cdot \Delta T
\]

**Equation 6.3**

\[
Q \left( \frac{W}{m^2} \right) = U \cdot \Delta T
\]

**Equation 6.4**

Where:
When it is necessary to evaluate energy consumption due to space heating or cooling it is employed the Cooling Degree Days and the Heating Degree Days. The Energy Performance Assessment (EPA) defines Cooling and Heating Degree Days as follows:

- **Cooling degree days** are used to estimate how hot the climate is and how much energy may be needed to keep buildings cool. CDDs are calculated by subtracting a balance temperature from the mean daily temperature, and summing only positive values over an entire year. The balance temperature used can vary, but is usually set at 65°F (18°C), 68°F (20°C), or 70°F (21°C).

- **Heating degree days** are used to estimate how cold the climate is and how much energy may be needed to keep buildings warm. HDDs are calculated by subtracting the mean daily temperature from a balance temperature, and summing only positive values over an entire year. The balance temperature used can vary, but is usually set at 65°F (18°C), 68°F (20°C), or 70°F (21°C).


Space heating and cooling in buildings depends on climate conditions, insulation, internal loads (lighting, TV, computers, people, freezers, ...) and ventilation.

Insulation reduces heat transfer through roofs, walls, floor and windows. Depending on the temperature difference between inside and outside the heat flows through the building envelope from inside to outside or vice versa.

Especially in Southern European countries, cooling demand becomes increasingly important for the overall energy consumption of a building due to higher requirements regarding thermal comfort. In warm climatic zones, demand for cooling can be drastically reduced by insulation. For an office building located in Madrid, green roof insulation provided energy savings of 24% (ECOFYS, 2004). As a result CO₂ emissions were also reduced. Green roof was installed over an existing conventional roof, improving its ceiling insulation.

Next table provides several examples of average U-values for **conventional roof (bare roof)** in different European countries. Conventional roofs are usually concrete decks with some insulating materials above.
<table>
<thead>
<tr>
<th>Country</th>
<th>Source</th>
<th>U-value (W/m²) 2000-2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>MonMech2013</td>
<td>0.22</td>
</tr>
<tr>
<td>Belgium</td>
<td>TABULA</td>
<td>0.57</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>BPIE</td>
<td>0.30</td>
</tr>
<tr>
<td>Cyprus</td>
<td>CY-STAT</td>
<td>0.55</td>
</tr>
<tr>
<td>Czech Rep.</td>
<td>BPIE. TABULA. panel SCAN 2009</td>
<td>0.24</td>
</tr>
<tr>
<td>Denmark</td>
<td>BPIE. TABULA</td>
<td>0.14</td>
</tr>
<tr>
<td>Estonia</td>
<td>TABULA. BPIE</td>
<td>0.18</td>
</tr>
<tr>
<td>Finland</td>
<td>BPIE</td>
<td>0.18</td>
</tr>
<tr>
<td>France</td>
<td>BPIE. TABULA</td>
<td>0.22</td>
</tr>
<tr>
<td>Germany</td>
<td>IWU</td>
<td>0.22</td>
</tr>
<tr>
<td>Greece</td>
<td>RES-H</td>
<td>0.39</td>
</tr>
<tr>
<td>Hungary</td>
<td>BPIE</td>
<td>0.25</td>
</tr>
<tr>
<td>Ireland</td>
<td>CSO 2011</td>
<td>0.31</td>
</tr>
<tr>
<td>Italy</td>
<td>BPIE.TABULA</td>
<td>1.20</td>
</tr>
<tr>
<td>Latvia</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>Lithuania</td>
<td>RES-H. State Enterprise Centre of Registers</td>
<td>0.18</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>BPIE</td>
<td>0.25</td>
</tr>
<tr>
<td>Malta</td>
<td>ODYSSEE.BPIE. NSO. TABULA</td>
<td>1.81</td>
</tr>
<tr>
<td>Netherlands</td>
<td>RES-H</td>
<td>0.40</td>
</tr>
<tr>
<td>Poland</td>
<td>BPIE. TABULA</td>
<td>0.60</td>
</tr>
<tr>
<td>Portugal</td>
<td>BPIE</td>
<td>1.33</td>
</tr>
<tr>
<td>Romania</td>
<td>BPIE</td>
<td>1.00</td>
</tr>
<tr>
<td>Slovakia</td>
<td>BPIE.Slovak building standards</td>
<td>0.30</td>
</tr>
<tr>
<td>Slovenia</td>
<td>TABULA.BPIE</td>
<td>0.20</td>
</tr>
<tr>
<td>Spain</td>
<td>TABULA. ODYSSEE</td>
<td>0.54</td>
</tr>
<tr>
<td>Sweden</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>UK</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>Serbia</td>
<td>RS-STAT</td>
<td>0.45</td>
</tr>
<tr>
<td>Croatia</td>
<td>HR stat</td>
<td>0.29</td>
</tr>
</tbody>
</table>

*Table 6.2. U-values of average conventional roofs in European countries (2008)*

Green roofs are living vegetation installed on the roofs, layered with waterproof and root-resistant membranes, a drainage system, filter cloth, growing media and plants. They can block solar radiation, and reduce daily temperature variations and thermal ranges between summer and winter.

Modern roof greening has two main types: intensive and extensive. Extensive green roofs are shallower systems of 60-200 mm depth, with a weight of 60-150 kg/m², with lower capital cost, no added irrigation and lower maintenance. Intensive green roofs range from 150 to 1000 mm in depth, with a weight of 180-500 kg/m² and are able to support a wider range of plants, though demanding more maintenance.
The thermal effects of green roofs can be divided into two aspects (Sam C.M. Hui, 2009):

- **Direct effect to the building (internal):** the heat transfer through the roof to the building interior which is the concern on building energy use.

- **Indirect effect to the surrounding environment (external):** the heat transfer from the roof to the surrounding environment which is the concern for urban heat islands. When the urban temperature is reduced, it will benefit all the buildings in the area or city and enhance energy conservation.

Heat flux transfer of green roofs is governed by four mechanisms: shading, thermal insulation, evapotranspiration and thermal mass. The thermal and energy performance of green roofs has been studied worldwide using three different approaches: field experimentation, numerical studies, and a combination of laboratory or field experiments with numerical models. In general, of total solar radiation absorbed by the green roof, about 27% is reflected, 60% is absorbed by the plants and the soil through evaporation and 13% is transmitted into the soil.

Literature review studies indicate that green roofs can substantially reduce the roof surface temperatures and heat flux from a building roof. However, the results of these studies have a wide range of conclusive outcomes in the magnitude of heat flux and energy reduction. For example, a USA study of a two-storey building found that, as compared with a conventional flat membrane roof, the green roof can reduce the heat flux by 18% to 50%. However, a simulation study of a green roof on a 5-storey office building in Singapore showed annual energy consumption savings of 1% to 15% depending on characteristics of the green roof (Sam C.M. Hui, 2009).

Engineering University of Hong Kong carried out an investigation on three green roof sites with retrofitting green roof projects in existing government buildings: Ngau Tau Kok (NTK) Building, APB Centre 4/F and Yuen Long Govt Primary School (YLGPS) and one pilot green roof project proposed by the University in a school building: St. Bonaventure Catholic Primary School (SBCPS). These green roof sites represented different types of designs and situations for the application of extensive and semi-intensive green roofs (Sam C.M. Hui, 2009).

Based on a steady-state Fourier theory in one dimension, the U-values of the green roof sites were estimated (see table below). The contribution of the green roofs varies from 16% (10/F of APB Centre) to 42% (Yuen Long Government Primary School), depending on the soil thickness and roof construction.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Description*</th>
<th>U-Value (Q/m²K)</th>
<th>% Change**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NTK Building - bare roof</td>
<td>2,433</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NTK Building - green roof 100 mm soil &amp; short plants</td>
<td>1,772</td>
<td>-27,2</td>
</tr>
<tr>
<td></td>
<td>NTK Building - green roof 150 mm soil &amp; taller plants</td>
<td>1,646</td>
<td>-32,4</td>
</tr>
<tr>
<td>2a</td>
<td>APB Centre, 4/F - bare roof</td>
<td>1,228</td>
<td></td>
</tr>
<tr>
<td></td>
<td>APB Centre, 4/F - green roof 100 mm soil &amp; sedum plants</td>
<td>1,020</td>
<td>-16,9</td>
</tr>
<tr>
<td>2b</td>
<td>APB Centre, 10/F - bare roof</td>
<td>1,194</td>
<td></td>
</tr>
<tr>
<td></td>
<td>APB Centre, 10/F - green roof 100 mm soil &amp; sedum plants</td>
<td>0,997</td>
<td>-16,5</td>
</tr>
</tbody>
</table>
### Table 6.3. Major results of U-value calculations for different types of green roofs in Hong Kong (Sam C.M. Hui, 2009)

Heat transfer of roof elements depends on its insulation and ventilated space between the roof surface and the building interior. In these cases adding a green roof will provide no further significant increase in thermal resistance. The choice of materials in the planted part of the roof does not greatly influence in the thermal behavior of a thermally insulated roof (Sam C.M. Hui, 2009).

Usually, a green roof is installed with additional insulated material. In such case, insulation improvement is not just due to the soil and vegetable layers, but the new material installed. Table below shows U-values for the insulation of a modern commercial green roof which consists on: a semi-extensive green roof covering, a substrate to depth required, a filtration layer, a drainage layer, a roof barrier, a single-ply non-bituminous membrane, an insulant (*Kingspan Thermaroof TR26 LPC/FM*), 50 mm creed to falls, a vapour control layer, a 150 mm concret deck and a 12.5 mm plaster board fixed to 25x50 mm timber battens at 600 mm centers (see figure below).

![Figure 6.5. Semi-Intensive Green Roof Covering-Dense Concrete Deck (KINGSPAN, 2011)](image-url)
U-value varies with insulant thickness:

<table>
<thead>
<tr>
<th>Insulant Thickness (mm)</th>
<th>U-values (W/m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>0.25</td>
</tr>
<tr>
<td>80</td>
<td>0.24</td>
</tr>
<tr>
<td>90</td>
<td>0.22</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>105</td>
<td>0.19</td>
</tr>
<tr>
<td>110</td>
<td>0.18</td>
</tr>
<tr>
<td>115</td>
<td>0.17</td>
</tr>
<tr>
<td>120</td>
<td>0.17</td>
</tr>
<tr>
<td>125</td>
<td>0.16</td>
</tr>
<tr>
<td>130</td>
<td>0.16</td>
</tr>
<tr>
<td>135</td>
<td>0.15</td>
</tr>
<tr>
<td>140</td>
<td>0.14</td>
</tr>
<tr>
<td>150</td>
<td>0.14</td>
</tr>
<tr>
<td>75+80*</td>
<td>0.13</td>
</tr>
<tr>
<td>80+85*</td>
<td>0.12</td>
</tr>
<tr>
<td>90+90</td>
<td>0.11</td>
</tr>
<tr>
<td>100+100</td>
<td>0.10</td>
</tr>
</tbody>
</table>

* Where multiple layers of insulation of different thicknesses are used, the thickest layer should be installed as the outermost layer in the construction.

Table 6.4. U-values for the insulation of a Semi-Intensive Green Roof Covering-Dense Concrete Deck with Suspended Ceiling (KINGSPAN, 2011)


Building insulation determines the energy consumption in cooling and heating. This section shows a method to estimate how much energy and emissions can be saved by constructing a green roof over a conventional roof, according to the following mathematical:

\[
P_{SGR+CR} \left( \frac{W}{m^2} \right) = \Delta U \left( \frac{W}{m^2 \cdot K} \right) \cdot \Delta T \ (K)
\]

Equation 6.5

Where:

\[
P_{SGR+CR} = \text{unitary power savings by installing a green roof over a conventional roof} \left( \frac{W}{m^2} \right)
\]

\[
\Delta U = U_{CONVENTIONAL \ ROOF} \left( \frac{W}{m^2 \cdot K} \right) - U_{GREEN ROOF OVER THE CONVENTIONAL ROOF} \left( \frac{W}{m^2 \cdot K} \right)
\]

\[
\Delta T = \text{difference between outside and inside temperature in the building} \ (K)
\]

In order to know the real power saving, efficiency of the heat generation and distribution system must be considered. If a HVAG system (Heating, Ventilation and Air Conditioning System) is considered, then the mathematical expression used corresponds to:
In order to estimate U-value for the green roof, thermal conductivity and thickness of each layer which compounds the roof needs to be identified.

Regarding to $\Delta T$ calculation, this method considers outdoors and indoors temperature as follows:

- Outdoors temperature: CDDs and HDDs are calculated by using outdoors mean daily temperature. A representative 24-hour temperature profile is considered for each month. Temperature data can be found in official databases. However, obtaining more accurate savings, a monitoring system should be implemented in the building where the green roof is going to be installed. In this way, accurate data of $\Delta T$ and energy savings can be obtained and U-value for the green roof can be calculated.

- Indoors temperature: to simplify calculations of $\Delta T$, it can be considered just two different setpoints: summer and winter. In this way, in summer HVAC system only works when the temperature outside the building is higher than summer setpoint temperature. In the same way, in winter HVAC system only works when the temperature outside the building is lower than winter setpoint temperature.

Furthermore, HVAC systems are not working 24 hours per day, instead they are usually operating during working hours. Therefore, a daily schedule should be considered as well as the number of working days in each month.

### 6.4.1. Winter

Average energy savings per m$^2$ of green roof during each hour of a representative day of a winter month can be calculated as follows:

$$P_{GR+CR} (\frac{W}{m^2}) = \Delta U \left( \frac{W}{m^2 \cdot K} \right) \cdot \Delta T \ (K) \cdot \frac{1}{\eta_{HVAC}}$$

**Equation 6.6**

Where:

$\eta_{HVAC} = efficiency \ of \ the \ HVAC \ system$

$\Delta U = U_{CONVENTIONAL \ ROOF} \left( \frac{W}{m^2 \cdot K} \right) - U_{GREENROOF \ OVER \ THE \ CONVENTIONAL \ ROOF} \left( \frac{W}{m^2 \cdot K} \right)$

$\Delta T = difference \ between \ outside \ and \ inside \ temperature \ in \ the \ building \ (K)$
\[
\text{ENS}_{ij} \left( \frac{\text{Wh}}{m^2} \right) = \Delta U \left( \frac{W}{m^2 \cdot K} \right) \cdot \Delta T(K) \cdot \frac{1}{\eta_{\text{HVACwinter}}} = \\
= \Delta U \cdot \left( T_{\text{winter setpoint}} - T_{\text{outdoors}_{ij}} \right) \cdot \frac{1}{\eta_{\text{Boiler}}} \cdot \text{use share}_{\text{Boiler}} \cdot \frac{100}{1} + \Delta U \cdot \left( T_{\text{winter setpoint}} - T_{\text{outdoors}_{ij}} \right) \cdot \frac{1}{\eta_{\text{Heat pump}}} \cdot \text{use share}_{\text{Heat pump}} \cdot \frac{100}{1}
\]

Equation 6.7

Where:

\[ i = \text{hour (0 h... 23 h)} \]

\[ j = \text{winter month (November... April)} \]

\[ \text{ENS}_{ij} = \text{average unitary energy savings during the hour } i \text{ of a representative day of the winter month } j \left( \frac{\text{Wh}}{m^2} \right) \]

\[ \Delta U = U_{\text{CONVENTIONAL ROOF}} \left( \frac{W}{m^2 \cdot K} \right) - U_{\text{GREEN ROOF OVER THE CONVENTIONAL ROOF}} \left( \frac{W}{m^2 \cdot K} \right) \]

\[ \Delta T = \text{difference between outside and inside temperature in the building (K)} \]

\[ T_{\text{winter setpoint}} = \text{set temperature in the HVAC System in winter (K)} \]

\[ T_{\text{outdoors}_{ij}} = \text{average temperature outside the building during the hour } i \text{ of a representative day of the winter month } j (K) \]

\[ \eta_{\text{HVACwinter}} = \text{efficiency of the HVAC system in winter} \approx \eta_{\text{Boiler}} = \text{boiler efficiency or } \eta_{\text{Heat Pump}} = \text{Heat Pump efficiency} \]

\[ \text{use share}_{\text{Boiler}} = \text{use share of the boiler in winter (}) % \]

\[ \text{use share}_{\text{Heat Pump}} = \text{use share of the heat pump in winter (}} % \]

Average energy savings per m\(^2\) of green roof during a representative day of a winter month can be calculated as follows:

\[
\text{ENS}_j \left( \frac{\text{Wh}}{m^2 \cdot \text{day}} \right) = \sum \text{ENS}_{ij} \left( \frac{\text{Wh}}{m^2} \right)
\]

Equation 6.8

Where:

\[ \text{ENS}_j = \text{average unitary energy savings during one representative day of the winter month } j \left( \frac{W}{m^2} \right) \]
\[ ENS_{ij} = \text{average unitary energy savings during the hour } i \text{ of a representative day of the winter month } j \left( \frac{W h}{m^2} \right) \]

Average energy savings per \( m^2 \) of green roof during the winter can be calculated as follows:

\[
ENS_{\text{winter}} \left( \frac{kW h}{m^2} \right) = \frac{\sum \left( ENS_j \left( \frac{W h}{m^2 \cdot \text{day}} \right) \cdot N_{\text{working days}_j} (\text{day}) \right)}{1000}
\]

Equation 6.9

Where:

\[ j = \text{winter months} \]

\[ ENS_{\text{winter}} = \text{average unitary energy savings during the winter} \left( \frac{kW h}{m^2} \right) \]

\[ ENS_j = \text{average unitary energy savings during one representative day of the winter month } j \left( \frac{W}{m^2} \right) \]

\[ N_{\text{working days}_j} = \text{number of working days in the winter month } j \text{ (days)} \]

Average emissions savings per \( m^2 \) of green roof during each hour of a representative day of a winter month can be calculated as follows:

\[
ES_{ij} \left( \frac{kg \ CO_2e}{m^2} \right) = \\
= \Delta U \cdot \left( T_{\text{winter setpoint}} - T_{\text{outdoors}_{ij}} \right) \cdot \frac{1}{\eta_{\text{Boiler}}} \cdot \frac{\text{use share}_{\text{Boiler}}}{100} \cdot EF_{\text{fuel}} + \Delta U \\
\cdot \left( T_{\text{winter setpoint}} - T_{\text{outdoors}_{ij}} \right) \cdot \frac{1}{\eta_{\text{Heat pump}}} \cdot \frac{\text{use share}_{\text{Heat pump}}}{100} \cdot EF_{\text{elec.concrete}}
\]

Equation 6.10

Where:

\[ i = \text{hour (0 h... 23 h)} \]

\[ j = \text{winter month (November... April)} \]

\[ ES_{ij} = \text{average unitary emissions savings during the hour } i \text{ of a representative day of the winter month } j \left( \frac{kg \ CO_2e}{m^2} \right) \]
Average emissions savings per m² of green roof during a representative day of a winter month can be calculated as follows:

\[
ES_j \left(\frac{kg \ CO_2 e}{m^2 \cdot day}\right) = \sum ES_{ij} \left(\frac{kg \ CO_2 e}{m^2}\right)
\]

Where:
- \(ES_j\) = average emissions savings during one representative day of the winter month \(j\) \(\left(\frac{kg \ CO_2 e}{m^2}\right)\)
- \(ES_{ij}\) = average unitary emissions savings during the hour \(i\) of a representative day of the winter month \(j\) \(\left(\frac{kg \ CO_2 e}{m^2}\right)\)

Average emissions savings per m² of green rooftop during the winter can be calculated as follows:

\[
ES_{\text{winter}} \left(\frac{kg \ CO_2 e}{m^2}\right) = \frac{\sum (ES_j \left(\frac{kg \ CO_2 e}{m^2 \cdot day}\right) \cdot N_{\text{working days}_j}\text{(day)})}{1000}
\]

Where:
- \(j\) = winter months
- \(ES_{\text{winter}}\) = average unitary emissions savings during the winter \(\left(\frac{kg \ CO_2 e}{m^2}\right)\)
- \(ES_j\) = average emissions savings during one representative day of the winter month \(j\) \(\left(\frac{kg \ CO_2 e}{m^2}\right)\)
- \(N_{\text{working days}_j}\) = number of working days in the winter month \(j\) (days)

6.4.2. Summer

Similar process can be used to calculate the average energy savings per m² of green roof during the summer.
Average energy savings per m² of green roof during each hour of a representative day of a summer month can be calculated as follows:

\[
E_{NSij} \left( \frac{Wh}{m^2} \right) = \Delta U \left( \frac{W}{m^2 \cdot K} \right) \cdot \Delta T \left( K \right) \cdot \frac{1}{\eta_{HVAC\_summer}} = \\
\Delta U \cdot (T_{outdoorsij} - T_{summer\_setpoint}) \cdot \frac{1}{\eta_{Heat\_Pump}}
\]

Where:

- \( i = \) hour (0 h... 23 h)
- \( j = \) summer month (May... October)
- \( E_{NSij} = \) average unitary energy savings during the hour \( i \) of a representative day of the summer month \( j \) (\( \frac{Wh}{m^2} \))
- \( U = U_{CONVENTIONAL\_ROOF} \left( \frac{W}{m^2 \cdot K} \right) - U_{GREEN\_ROOF\_OVER\_THE\_CONVENTIONAL\_ROOF} \left( \frac{W}{m^2 \cdot K} \right) \)
- \( \Delta T = \) difference between outside and inside temperature in the building (K)
- \( T_{summer\_setpoint} = \) set temperature in the HVAC System in summer (K)
- \( T_{outdoorsij} = \) average temperature outside the building during the hour \( i \) of a representative day of the summer month \( j \) (K)
- \( \eta_{HVAC\_summer} = \) efficiency of the HVAC system in summer \( \approx \eta_{Heat\_Pump} = \) heat pump efficiency

Average energy savings per m² of green roof during a representative day of a summer month can be calculated as follows:

\[
E_{NSj} \left( \frac{Wh}{m^2 \cdot day} \right) = \sum E_{NSij} \left( \frac{Wh}{m^2} \right)
\]

Where:

- \( E_{NSj} = \) average unitary energy savings during one representative day of the summer month \( j \) (\( \frac{Wh}{m^2} \))
- \( E_{NSij} = \) average unitary energy savings during the hour \( i \) of a representative day of the summer month \( j \) (\( \frac{Wh}{m^2} \))
Average energy savings per m$^2$ of green roof during the summer can be calculated as follows:

$$\text{ENS}_{\text{summer}} \ (kWh \ m^2) = \frac{\sum \left( \text{ENS}_j \left( \frac{W}{m^2 \cdot \text{day}} \right) \cdot N_{\text{working days}_j} \right) (\text{day})}{1000}$$  \hspace{1cm} \text{Equation 6.15}

Where:

\( j = \text{summer months} \)

\( \text{ENS}_{\text{summer}} = \text{average unitary energy savings during the summer} \ (kWh \ m^2) \)

\( \text{ENS}_j = \text{average unitary energy savings during one representative day of the summer month } j \ (W \ m^2) \)

\( N_{\text{working days}_j} = \text{number of working days in the summer month } j \ (\text{days}) \)

Average emissions savings per m$^2$ of green roof during the summer can be calculated as follows:

$$\text{ES}_{\text{summer}} \ (kg \ CO_2e \ m^2) = \text{ENS}_{\text{summer}} \ (kWh \ m^2) \cdot EF_{\text{elec. count.}} \ (kg \ CO_2e \ kWh)$$  \hspace{1cm} \text{Equation 6.16}

Where:

\( \text{ES}_{\text{summer}} \ (kg \ CO_2e \ m^2) = \text{average unitary emissions savings during the summer} \ (kg \ CO_2e \ m^2) \)

\( \text{ENS}_{\text{summer}} = \text{average unitary energy savings during the summer} \ (kWh \ m^2) \)

\( EF_{\text{elec. count.}} = \text{Emission factor for electricity production of a country or region} \ (kg \ CO_2e \ kWh) \)

### 6.4.3. Annual

Annual energy savings by installing a green roof over a conventional roof are calculated by adding both summer and winter energy savings:

$$\text{ENS}_{GR+CV \ VS. \ CV} \ (\frac{kWh}{m^2 \cdot \text{year}}) = \text{ENS}_{\text{winter}} + \text{ENS}_{\text{summer}}$$  \hspace{1cm} \text{Equation 6.17}

Where:
\[ E_{\text{NSGR+CV vs. CV}} = \text{annual average unitary energy savings by installing a greenroof over a conventional roof (} \frac{kW}{m^2} \) \]

\[ E_{\text{NSwinter}} = \text{average unitary energy savings during the winter (} \frac{kWh}{m^2} \) \]

\[ E_{\text{NSsummer}} = \text{average unitary energy savings during the summer (} \frac{kWh}{m^2} \) \]

**Annual emissions savings** are calculated by adding both summer and winter energy savings:

\[ E_{\text{NSGR+CV vs. CV}} \left( \frac{kg \ CO_2e}{m^2 \cdot \text{year}} \right) = E_{\text{NSwinter}} + E_{\text{NSsummer}} \]

*Equation 6.18*

Where:

\[ E_{\text{NSGR+CV vs. CV}} = \text{annual average unitary emissions savings by installing a greenroof over a conventional roof (} \frac{kg \ CO_2e}{m^2} \) \]

\[ E_{\text{NSwinter}} = \text{average unitary emissions savings during the winter (} \frac{kg \ CO_2e}{m^2} \) \]

\[ E_{\text{NSsummer}} = \text{average unitary emissions savings during the summer (} \frac{kg \ CO_2e}{m^2} \) \]
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