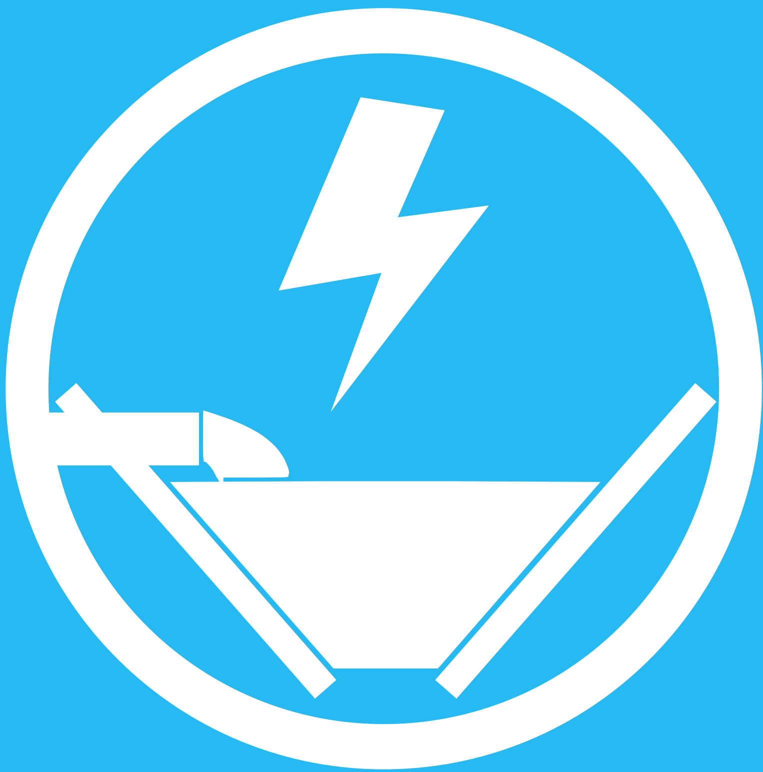
Report on Energy in the Urban Water Cycle



E²STORMED PROJECT
Improvement of energy efficiency in the water cycle by the use of innovative storm water management in smart Mediterranean cities
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UNIVERSITAT POLITÈCNICA DE VALÈNCIA

L'Europe en Méditerranée
Europe in the Mediterranean

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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.

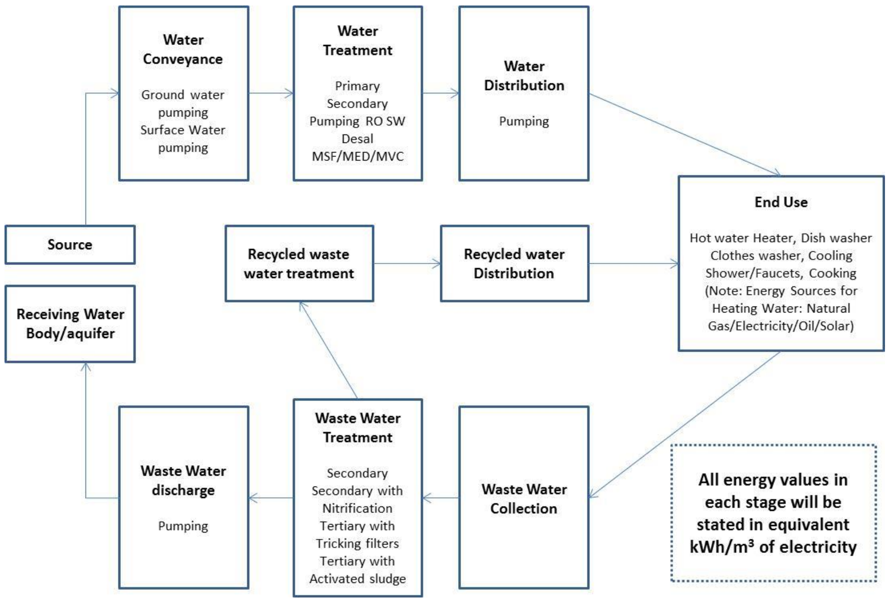

Figure 1.1. Stages of the water life cycle through the municipal sector (Wilkinson, 2000) and (Lienhard, 2010)

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 cube 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.

1.2. RELATION BETWEEN CO_2 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, CO_2 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 CO_2 emissions per kWh produced by the electricity generation system of each country, depending on the energy sources available at each region.

Country	2004	2005	2006	2007	2008	2009	2010
Albania	30	26	26	31	0	1	2
Armenia	114	131	130	157	159	102	92
Austria	224	218	217	204	187	158	188
Azerbaijan	677	650	671	570	534	499	439
Belarus	463	459	461	452	465	466	449
Belgium	285	275	263	254	254	218	220
Bosnia and Herzegovina	772	797	852	1007	830	806	723
Bulgaria	537	502	490	592	565	537	535
Croatia	**314**	**331**	**337**	**422**	**367**	**291**	**236**
Cyprus	772	788	758	761	759	743	697
Czech Republic	617	614	606	636	621	588	589
Denmark	403	369	459	425	398	398	360
Estonia	1029	1048	965	1048	1084	1078	1014
Finland	258	164	265	238	177	190	229
France	67	79	72	76	72	78	79
FYR of Macedonia	797	791	783	871	905	799	685
Georgia	89	101	147	161	79	123	69
Germany	503	486	483	504	476	467	461
Gibraltar	766	761	751	751	757	757	762
Greece	**780**	**779**	**731**	**752**	**748**	**725**	**718**
Hungary	448	372	373	368	351	313	317

Iceland	0	0	0	1	1	0	0
Ireland	575	584	537	510	471	452	458
Italy	**497**	**486**	**509**	**475**	**452**	**411**	**406**
Kazakhstan	584	570	839	658	541	433	403
Kosovo	1297	1121	1127	1089	1088	1286	1287
Kyrgyzstan	68	58	56	61	57	57	59
Latvia	97	89	113	107	114	96	120
Lithuania	68	101	100	88	83	84	337
Luxembourg	393	389	387	381	385	376	410
Malta	**913**	**1034**	**954**	**1012**	**849**	**850**	**872**
Montenegro	**..**	**341**	**386**	**352**	**456**	**274**	**405**
Netherlands	467	454	452	455	442	420	415
Norway	3	2	3	4	3	11	17
Poland	833	818	821	820	815	799	781
Portugal	465	521	431	396	394	379	255
Republic of Moldova	526	529	506	530	510	526	517
Romania	528	493	521	542	512	472	413
Russian Federation	402	436	445	428	426	402	384
Serbia	883	764	817	750	772	766	718
Slovak Republic	233	221	214	220	207	210	197
Slovenia	345	349	362	375	332	318	325
Spain	**382**	**397**	**369**	**387**	**327**	**297**	**238**
Sweden	23	19	23	17	18	19	30
Switzerland	28	32	33	30	29	26	27
Tajikistan	22	21	21	20	20	17	14
Turkey	426	438	452	494	511	496	460
Turkmenistan	872	872	872	872	927	865	954
Ukraine	360	397	430	440	447	390	392
United Kingdom	**491**	**491**	**515**	**506**	**499**	**453**	**457**
Uzbekistan	588	588	583	609	543	566	550
European Union[27]	**391**	**387**	**391**	**395**	**374**	**357**	**347**

Table 1.1. CO_2 Emissions (g CO_2 per kWh) per country due to electricity consumption (IEA, 2012)

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

CO_2 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:

Fuel		**Lower heating Value**	**Energy basis**	**Mass basis**	**Liquid basis**	**Gas basis**	**Energy**
		TJ/Gg	***$kgCO_2e/TJ$***	***$kgCO_2e$/ tonne***	***$kgCO_2e$/ litre***	***$kgCO_2e/m^3$***	***$kgCO_2e$/ kWh***
Oil products	Crude oil	42.3	73300	3101	2.48		0.26
	Orimulsion	27.5	77000	2118			0.28

	Natural Gas Liquids	44.2	64200	2838			0.23
	Motor gasoline	44.3	69300	3070	2.27		0.25
	Aviation gasoline	44.3	70000	3101	2.20		0.25
	Jet gasoline	44.3	70000	3101	2.20		0.25
	Jet kerosene	44.1	71500	3153	2.49		0.26
	Other kerosene	43.8	71900	3149	2.52		0.26
	Shale oil	38.1	73300	2793	2.79		0.26
	Gas/Diesel oil	43	74100	3186	2.68		0.27
	Residual fuel oil	40.4	77400	3127	2.94		0.28
	Liquified Petroleum Gases	47.3	63100	2985	1.61		0.23
	Ethane	46.4	61600	2858		3.72	0.22
	Naphtha	44.5	73300	3262	2.51		0.26
	Bitumen	40.2	80700	3244			0.29
	Lubricants	40.2	73300	2947	2.95		0.26
	Petroleum coke	32.5	97500	3169			0.35
	Refinery feedstocks	43	73300	3152			0.26
	Refinery gas	49.5	57600	2851			0.21
	Paraffin waxes	40.2	73300	2947			0.26
	White Spirit/SBP	40.2	73300	2947			0.26
	Other petroleum products	40.2	73300	2947			0.26
Coal products	Anthracite	26.7	98300	2624.61			0.35
	Coking coal	28.2	94600	2667.72			0.34
	Other bituminous coal	25.8	94600	2440.68			0.34
	Sub bituminous coal	18.9	96100	1816.29			0.35
	Lignite	11.9	101000	1201.9			0.36
	Oil shale and tar sands	8.9	107000	952.3			0.39
	Brown coal briquettes	20.7	97500	2018.25			0.35
	Patent fuel	20.7	97500	2018.25			0.35
	Coke oven coke	28.2	107000	3017.4			0.39
	Lignite coke	28.2	107000	3017.4			0.39
	Gas coke	28.2	107000	3017.4			0.39
	Coal tar	28	80700	2259.6			0.29
	Gas works gas	38.7	44400	1718.28			0.16
	Coke oven gas	38.7	44400	1718.28			0.16
	Blast furnace gas	2.47	260000	642.2			0.94
	Oxygen steel furnace gas	7.06	182000	1284.92			0.66
Natural gas	Natural gas	48	56100	2692.8		1.88	0.20
Other wastes	Municipal waste (Non biomass fraction)	10	91700	917.00			0.33
	Industrial wastes	NA	143000	NA			0.51
	Waste oils	40.2	73300	2946.66			0.26

Biomass	Wood or Wood waste	15.6	112000	1747.2			0.40
	Sulphite lyes (Black liqour)	11.8	95300	1124.54			0.34
	Other primary solid biomass fuels	11.6	100000	1160			0.36
	Charcoal	29.5	112000	3304			0.40
	Biogasoline	27	70800	1911.6			0.25
	Biodiesels	27	70800	1911.6			0.25
	Other liquid biofuels	27.4	79600	2181.04			0.29
	Landfill gas	50.4	54600	2751.84		2.47	0.20
	Sludge gas	50.4	54600	2751.84			0.20
	Other biogas	50.4	54600	2751.84			0.20
	Municipal wastes (Biomass fraction)	11.6	100000	1160			0.36
	Peat	9.76	106000	1034.56			0.38

Table 1.2. CO_2 Emissions (g CO_2 per kWh) per (g CO_2 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 CO_2 emissions associated, as this expresses the potential of global warning. 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 CO_2 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, m^2 or m^3, which is also associated to an energy used and CO_2 emission factor per material manufacturing. There exist several CO_2 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.

1513_01 - CUBIERTA PLANA AJARDINADA (E)

Parámetros: Precios España, Enero 2013, Coste Directo, Obras tipo (PEM 1,621 M euros) **Pliegos** España; **Definición** descripción incluyendo productos comerciales, sin criterio de medición;

TCQ **15131590 m2 Cubierta plana ajardinada extensiva convencional, formación de pendientes con hormigón celular, impermeabilización y protección antiraíces con membrana formada de dos láminas una LBM (SBS)-30- FV y la otra LBM (SBS)- 50/ G- FP, capa separadora con geotextil, capa retenedora y drenante con lámina nodular de polietileno de alta densidad, capa filtrante con geotextil y sustrato de tierra vegetal de 10 cm de espesor 73,73 € (J,MA)**

Consumo	Peso	Costo energètico		Emisión CO2
	Kg	MJ	kwh	Kg
Componentes constitutivos de materiales	200,97	641,97	178,32	99,01
aditivo espumante	0,25	25,25	7,01	3,73
agua	23,12	0,14	0,039	0,0067
árido	132,44	19,87	5,52	1,06
betún asfáltico	7,57	333,96	92,77	49,06
cemento	24,54	92,71	25,75	20,44
lana de vidrio	0,066	3,21	0,89	0,097
materia vegetal	11,11	-	-	-
poliéster	0,51	27,48	7,63	4,06
polietileno	1,37	139,35	38,71	20,57
Componentes constitutivos de maquinaria	-	0,33	0,092	0,048
eléctrica	-	0,33	0,092	0,048
Total	200,97	642,30	178,42	99,06

Residuo	Peso (Kg)	Volumen (m3)

Cerrar

Table 2.1. "Construmática" example of greenroof materials

Environment Agency

Category	Specific material	Own data: density of material	Base data: density of material	Own data for tCO_2e/t material	Base data: tCO_2e/t material	Boundaries	Source ref.
Quarried Material	Quarried aggregate	tonnes/m3	**2.0** tonnes/m3		0.005	cradle to gate	3
	Recycled aggregate	tonnes/m3	**2.0** tonnes/m3		0.005	cradle to gate	3
	Marine aggregate	tonnes/m3	**2.0** tonnes/m3		0.008	cradle to gate	9
	Asphalt, 4% (bitumen) binder content (by mass)	tonnes/m3	**1.7** tonnes/m3		0.066	cradle to gate	1
	Asphalt, 5% (bitumen) binder content	tonnes/m3	**1.7** tonnes/m3		0.071	cradle to gate	1
	Asphalt, 6% (bitumen) binder content	tonnes/m3	**1.7** tonnes/m3		0.076	cradle to gate	1
	Asphalt, 7% (bitumen) binder content	tonnes/m3	**1.7** tonnes/m3		0.081	cradle to gate	1
	Asphalt, 8% (bitumen) binder content	tonnes/m3	**1.7** tonnes/m3		0.086	cradle to gate	1
	Bitumen	tonnes/m3	**2.4** tonnes/m3		0.49	cradle to gate	1
	Bricks	tonnes/m3	**1.9** tonnes/m3		0.24	cradle to gate	1
	Clay: general (simple baked products)	tonnes/m3	**1.9** tonnes/m3		0.24	cradle to gate	1
	Clay tile	tonnes/m3	**1.9** tonnes/m3		0.48	cradle to gate	1
	Vitrified clay pipe DN 100 & DN 150	tonnes/m3	**2.4** tonnes/m3		0.46	cradle to gate	1
	Vitrified clay pipe DN 200 & DN 300	tonnes/m3	**2.4** tonnes/m3		0.50	cradle to gate	1
	Vitrified clay pipe DN 500	tonnes/m3	**2.4** tonnes/m3		0.55	cradle to gate	1
	Ceramics: general	tonnes/m3	**2.4** tonnes/m3		0.7	cradle to gate	1
	Ceramics: Tiles and Cladding Panels	tonnes/m3	**1.9** tonnes/m3		0.78	cradle to gate	1
	Sand	tonnes/m3	**2.24** tonnes/m3		0.0051	cradle to gate	1
	Lime	tonnes/m3	**1.2** tonnes/m3		0.78	cradle to gate	1
	Soil - general / rammed soil	tonnes/m3	**1.7** tonnes/m3		0.024	cradle to gate	1
	Stone: general	tonnes/m3	**2.0** tonnes/m3		0.079	cradle to gate	1
	Granite	tonnes/m3	**2.9** tonnes/m3		0.7	cradle to gate	1
	Limestone	tonnes/m3	**2.2** tonnes/m3		0.09	cradle to gate	1
	Sandstone	tonnes/m3	**2.2** tonnes/m3		0.06	cradle to gate	1
	Shale	tonnes/m3	**2.7** tonnes/m3		0.002	cradle to gate	1
	Slate	tonnes/m3	**1.6** tonnes/m3		0.035	cradle to gate	1

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 CO_2 emissions related to the construction of a drainage system are expressed in kWh and kg CO_2e per size unit, respectively. Size Units are m, m^2 or m^3 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.

	Type of drainage infrastructure	Size Considered	Unit	Construction		Periodic maintenance		Annual Maintenance		
				Energy kWh/unit	*Emissions* $kgCO_2$/unit	*Energy* kWh/unit	*Emissions* $kgCO_2$/unit	*n.trips* trips/year	*Energy* kWh/unit	*Emissions* $kgCO_2$/unit
Conventional Urban Drainage Systems	Sewer Pipes	1	m	32.3	9.6	0	0	1	4.012	1.072
	Standard Pavement	1	m^2	164.7	52.1	0.0004	0.0001	1	4.012	1.072
	Structural Detention Facilities	1	m^3	849.3	269.0	0	0	2	8.024	2.144
	Conventional Roof	1	m^2	123.1	37.3	0	0	1	4.012	1.072
Sustainable Urban Drainage Systems	Vegetated Swales	616.64	m^2	42.8	13.4	0.1853	0.0488	6	0.039	0.010
	Filter Drains	9	m^3	101.3	32.0	6.8836	1.8136	2	0.892	0.238
	Infiltration trenches	9	m^3	55.7	17.1	6.8836	1.8136	2	0.892	0.238
	Soakaways	9	m^3	52.1	16.1	5.4993	1.4489	2	0.892	0.238
	Filter Strips	280	m^2	11.6	3.4	0	0	12	0.172	0.046
	Permeable Pavement	1	m^2	92.2	29.2	0.0014	0.0004	2	8.024	2.144
	Retention Ponds	287	m^3	36.8	11.1	0.0063	0.0017	2	0.028	0.007
	Detention Basins	462	m^3	25.5	7.5	0.0039	0.001	2	0.017	0.005
	Infiltration Basins	462	m^3	15.7	4.3	0.0039	0.001	2	0.017	0.005
	Rain gardens	32	m^2	118.0	36.0	0.0987	0.026	12	1.505	0.402
	Bioretention Areas	200	m^2	137.1	42.3	0.0987	0.026	12	0.241	0.064
	Constructed Wetlands	143	m^2	71.9	10.8	0.0126	0.0033	2	0.056	0.015
	Rainwater Harvesting System	4	m^3	245.4	80.6	0	0	2	2.006	0.536
	Water butts	0.5	m^3	242.0	79.9	0	0	2	16.048	4.288
	Green Roof	1	m^2	93.3	28.1	0	0	2	8.024	2.144
	Geocellular Systems	1	m^3	1011.9	328.6	0	0	2	8.024	2.144

Table 2.3. Energy Consumption and CO_2 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 CO_2 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:

- <u>Technical description:</u> 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.
- <u>Dimensions:</u> 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

- <u>Machinery</u>

Two forms of energy have been identified:

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

- <u>Materials:</u>

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:

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

Equation 2.1

Where:

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

$i = work\ unit$

$P_{elec.mach.} = Electric\ machinery\ average\ power(kW)$

$OT_{elec.mach.} = Operation\ time\ of\ electrical\ machinery\ \left(\frac{h}{work\ unit}\right)$

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

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

Equation 2.2

Where:

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

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

As an example, emission factor of EU-27 of electricity for 2010 is 0.347 kgCO_2/kWh.

Fuel for a work unit

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

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

Equation 2.3

Where:

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

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

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

Then, emissions can be calculated as follows:

$$E_{fuel\ mach._i}\left(\frac{kg\ CO_2e}{work\ unit}\right) = \sum_k \left[EC_{fuel\ mach.\_k}\left(\frac{kWh}{work\ unit}\right) \cdot EF_{fuel\_k}\left(\frac{kg\ CO_2e}{kWh}\right)\right]$$

Equation 2.4

Where:

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

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

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:

$$EC_{mach._i}\left(\frac{kWh}{work\ unit}\right) = EC_{elec.\ mach._i}\left(\frac{kWh}{work\ unit}\right) + EC_{fuel\ mach._i}\left(\frac{kWh}{work\ unit}\right)$$

Equation 2.5

Where:

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

In the same way, emissions from the same work unit can be calculated as follows:

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

Equation 2.6

Where:

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

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:

$$UEC_{mach.\ DRAINAGE\ SYSTEM}\left(\frac{kWh}{size\ unit}\right) = \sum_i \left[EC_{mach._i}\left(\frac{kWh}{work\ unit}\right) \cdot Q_i\left(\frac{work\ unit}{size\ unit}\right)\right]$$

Equation 2.7

Where:

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

$$Q_i = Quantity\ of\ work\ unit\ per\ unitary\ size\ of\ a\ draiange\ system\left(\frac{work\ unit}{size\ unit}\right)$$

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

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

Equation 2.8

Where:

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

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:

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

Equation 2.9

Where:

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

$S_{DRAINAGE\ SYSTEM} = size\ of\ the\ drainage\ system\ (size\ unit)$

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

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

Equation 2.10

Where:

$E_{mach. DRAINAGE\ SYSTEM} = Emissions\ by\ machinery\ used\ in\ the\ construction\ of\ a\ drainage\ system (kg\ CO_2e)$

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:

$$ECF_{material}\left(\frac{kWh}{material\ unit}\right) = EE_{material}\left(\frac{MJ}{kg}\right)\cdot\frac{1kWh}{3{,}6MJ}\cdot D_{material}\left(\frac{kg}{material\ unit}\right) \quad \textit{Equation 2.11}$$

Where:

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

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

$$D_{material} = Material\ Density\ \left(\frac{kg}{material\ unit}\right)$$

To continue, next two sections provide a description of the method for estimating energy consumption and CO_2 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:

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

Where:

$ECF_{elect\cdot material} = Electric\ Energy\ Consumption\ \ Factor\ of\ a\ material\ \left(\frac{kWh}{material\ unit}\right)$

$ES_{material} = Electricity\ share\ in\ \ the\ manufacturing\ industry\ of\ the\ material\ (\%)$

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

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

Where:

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

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

Fuel for a work unit (in material production processes)

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

$$ECF_{fuel_{material}}\left(\frac{kWh}{material\ unit}\right) = ECF_{material}\left(\frac{kWh}{material\ unit}\right) \cdot \frac{FS_{material}\ (\%)}{100}$$

Equation 2.14

Where:

$$ECF_{fuel_{material}} = Electric\ Energy\ Consumption\ \ Factor\ of\ a\ material\ \left(\frac{kWh}{material\ unit}\right)$$

$$FS_{material} = Fuel\ share\ in\ \ the\ manufacturing\ industry\ of\ the\ material\ (\%)$$

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

$$E_{fuel_{material}}\left(\frac{kg\ CO_2e}{material\ unit}\right) = ECF_{fuel\ _{material}}\left(\frac{kWh}{material\ unit}\right) \cdot EF_{fuel}\left(\frac{kg\ CO_2e}{kWh}\right)$$

Equation 2.15

Where:

$$E_{elect.material} = Emissions\ by\ fuel\ processes\ in\ the\ manufacturing$$

$$of\ \ a\ material\ unit\left(\frac{kg\ CO_2e}{material\ unit}\right)$$

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

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:

$$E_{material}\left(\frac{kg\ CO_2e}{material\ unit}\right) = E_{elect.material}\left(\frac{kg\ CO_2e}{material\ unit}\right) + E_{fuel_{material}}\left(\frac{kg\ CO_2e}{material\ unit}\right)$$

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:

$$UEC_{material\,DRAINAGE\ SYSTEM}\left(\frac{kWh}{size\ unit}\right) = \sum\left[ECF_{material}\left(\frac{kWh}{material\ unit}\right)\cdot Q_{material}\left(\frac{material\ unit}{size\ unit}\right)\right]$$

Equation 2.17

Where:

$$UEC_{material\,DRAINAGE\ SYSTEM} = Energy\ consumption\ in\ material\ manufacturing\ per\ Unitary\ size\ of\ a\ drainage\ system\left(\frac{kWh}{size\ unit}\right)$$

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

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

$$UE_{material\ DRAINAGE\ SYSTEM}\left(\frac{kg\ CO_2e}{size\ unit}\right) = \sum\left[E_{material}\ \left(\frac{kg\ CO_2e}{material\ unit}\right)\cdot\ Q_{material}\left(\frac{material\ unit}{size\ unit}\right)\right]$$

Equation 2.18

Where:

$$UE_{material\,DRAINAGE\ SYSTEM} = Emissions\ in\ material\ manufacturing\ per\ Unitary\ size\ of\ a\ drainage\ system\left(\frac{kg\ CO_2e}{size\ unit}\right)$$

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:

$$EC_{material\ DRAINAGE\ SYSTEM}\ (kWh) = UEC_{material\ DRAINAGE\ SYSTEM}\ \left(\frac{kWh}{size\ unit}\right) \cdot S_{DRAINAGE\ SYSTEM}\ (size\ unit) \qquad \textit{Equation 2.19}$$

Where:

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

$S_{DRAINAGE\ SYSTEM} = size\ of\ the\ drainage\ system\ (size\ unit)$

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

$$E_{material\ DRAINAGE\ SYSTEM}\ (kg\ CO_2e) = UE_{material\ DRAINAGE\ SYSTEM}\ \left(\frac{kg\ CO_2e}{size\ unit}\right) \cdot S_{DRAINAGE\ SYSTEM}\ (size\ unit) \qquad \textit{Equation 2.20}$$

Where:

$E_{material\,DRAINAGE\ SYSTEM} =$ Emissions in material manufacturing of construction of a drainage system$(kg\ CO_2e)$

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:

$$EC_{Construction\ DRAINAGE\ SYSTEM}\ (kWh) = EC_{mach.\ DRAINAGE\ SYSTEM}\ (kWh) + EC_{material\ DRAINAGE\ SYSTEM}\ (kWh)$$

Equation 2.21

Where:

$EC_{Construction\ DRAINAGE\ SYSTEM} = Energy\ consumption\ in\ the\ construction\ of\ a\ drainage\ system (kWh)$

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

$$E_{Construction\ DRAINAGE\ SYSTEM}\ (kg\ CO_2e) = E_{mach.\ DRAINAGE\ SYSTEM}\ (kg\ CO_2e) + E_{material\ DRAINAGE\ SYSTEM}\ (kg\ CO_2e)$$

Equation 2.22

Where:

$E_{Construction\ DRAINAGE\ SYSTEM} = Emissions\ in\ the\ construction\ of\ a\ drainage\ system (kg\ CO_2e)$

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:

	Type of drainage infrastructure	Trips per year
Conventional Urban Drainage Systems	Sewer Pipes	1
	Standard Pavement	1
	Structural Detention Facilities	2
	Conventional Roof	1
Sustainable Urban Drainage Systems	Vegetated Swales	6
	Filter Drains	2
	Infiltration trenches	2
	Soakaways	2
	Filter Strips	12
	Permeable Pavement	2
	Retention Ponds	2
	Detention Basins	2
	Infiltration Basins	2
	Rain gardens	12
	Bioretention Areas	12
	Constructed Wetlands	2
	Rainwater Harvesting System	2
	Water butts	2
	Green Roof	2
	Geocellular Systems	2

Table 2.4. Number of trips per year considered for Annual Maintenance (SFPUC, 2013).

Hence, energy consumption in the annual maintenance of a drainage system is therefore calculated as follows:

$$EC_{ann.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kWh}{year}\right) = FC_{vehicle}\left(\frac{l\ fuel}{km}\right)\cdot d_{trip}\left(\frac{km}{trip}\right)\cdot N_{trips}\left(\frac{trip}{year}\right)\cdot ENF_{fuel}\left(\frac{kWh}{l\ fuel}\right) \quad \text{Equation 2.23}$$

Where:

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

$FC_{vehicle} = Vehicle\ fuel\ consumption\ \left(\frac{l\ fuel}{km}\right)$

$N_{trips} = Annual\ number\ of\ trips\ \left(\frac{trip}{year}\right)$

$ENF_{fuel} = Fuel\ energy\ factor\ \left(\frac{kWh}{l\ fuel}\right)$

$$d_{trip} = Typical\ Distance\ covered\ per\ trip\ \left(\frac{km}{trip}\right)$$

Typical distance covered per trip, d_{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:

$$E_{ann.maint.\ DRAINAGE\ SYSTEM}\ \left(\frac{kg\ CO_2e}{year}\right) = FC_{vehicle}\left(\frac{l\ fuel}{km}\right)\cdot d_{trip}\left(\frac{km}{trip}\right)\cdot N_{trips}\left(\frac{trip}{year}\right)\cdot EF_{fuel}\left(\frac{kg\ CO_2e}{l\ fuel}\right) \quad \text{Equation 2.24}$$

Where:

$$E_{ann.maint.\ DRAINAGE\ SYSTEM} = Emissions\ in\ the\ annual\ maintenance\ of\ a\ drainage\ system\ \left(\frac{kg\ CO_2e}{year}\right)$$

$$EF_{fuel} = Fuel\ emission\ factor\ \left(\frac{kg\ CO_2e}{l\ fuel}\right)$$

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_2e/*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 reinstallation 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.

DRAINAGE SYSTEM	PERIODIC MAINTENANCE TASK	EF, UNITS	EF, VALUE	FREQ., YEARS	EF, YEAR EQUIV.
Sewer Pipes	-				
Standard Pavement	>> Remove and reinstall block pavement and install new geotextile	($kgCO_2e/m^2$)	0.5	25	0.020
Structural Detention Facilities	-				
Conventional Roof	-				
Vegetated Swales	>> Clear vegetation from swale & dispose of arisings off site >> De-silting of swale	($kgCO_2e/m$) ($kgCO_2e/m$)	0.395 1.755	5 5	0.079 0.351
Filter Drains	>> Remove, dispose and replace top gravel layer >> Install new geotextile	($kgCO_2e/m^3$) ($kgCO_2e/m^2$)	13.57 2.73	5 5	3 0.546
Infiltration trenches	>> Remove, dispose and replace top gravel layer >> Install new geotextile	($kgCO_2e/m^3$) ($kgCO_2e/m^2$)	13.57 2.73	5 5	2.714 0.546
Soakaways	>> Remove, dispose and replace top gravel layer >> Install new geotextile	($kgCO_2e/m^3$) ($kgCO_2e/m^2$)	13.57 2.73	5 5	2.714 0.546
Filter Strips	-				-
Permeable Pavement	>> Remove and reinstall block pavement and install new geotextile	($kgCO_2e/m^2$)	1.84	25	0.074
Retention Ponds	>> De-silting & dispose sediments off site	($kgCO_2e/m^3$)	4.57	5	0.914
Detention Basins	>> De-silting & dispose sediments off site	($kgCO2e/m^3$)	4.57	5	0.914
Infiltration Basins	>> De-silting & dispose sediments off site	($kgCO_2e/m^3$)	4.57	5	0.914
Rain gardens	>> Removal and replacement of silt covered vegetation	($kgCO_2e/m^2$)	0.13	5	0.026
Bioretention areas	>> Removal and replacement of silt covered vegetation	($kgCO_2e/m^2$)	0.13	5	0.026
Constructed Wetlands	>> De-silting of forebay & dispose sediments off site	($kgCO_2e/m^3$)	4.57	5	0.914
Complex Rainwater Harvesting System	-		-	-	-
Water butts	-		-	-	-
Green Roof	-		-	-	-
Geocellular Systems	-		-	-	-

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).

DRAINAGE SYSTEM	PERIODIC MAINTENANCE TASK	ENF, UNITS	ENF, VALUE	FREQ., YEARS	ENF, YEAR EQUIV.
Sewer Pipes	-				
Standard Pavement	>> Remove and reinstall block pavement and install new geotextile	(kWh/m^2)	0.132	25	0.005
Structural Detention Facilities	-				
Conventional Roof	-				
Vegetated Swales	>> Clear vegetation from swale & dispose of arisings off site >> De-silting of swale	(kWh/m) (kWh/m)	1.500 6.661	5 5	0.300 1.332
Filter Drains	>> Remove, dispose and replace top gravel layer >> Install new geotextile	(kWh/m^3) (kWh/m^2)	51.505 10.362	5 5	10 2.072
Infiltration trenches	>> Remove, dispose and replace top gravel layer >> Install new geotextile	(kWh/m^3) (kWh/m^2)	51.505 10.362	5 5	10.301 2.072
Soakaways	>> Remove, dispose and replace top gravel layer >> Install new geotextile	(kWh/m^3) (kWh/m^2)	51.505 10.362	5 5	10.301 2.072
Filter Strips	-		-		-
Permeable Pavement	>> Remove and reinstall block pavement and install new geotextile	(kWh/m^2)	6.984	25	0.279
Retention Ponds	>> De-silting & dispose sediments off site	(kWh/m^3)	17.346	5	3.469
Detention Basins	>> De-silting & dispose sediments off site	(kWh/m^3)	17.346	5	3.469
Infiltration Basins	>> De-silting & dispose sediments off site	(kWh/m^3)	17.346	5	3.469
Rain gardens	>> Removal and replacement of silt covered vegetation	(kWh/m^2)	0.493	5	0.099
Bioretention areas	>> Removal and replacement of silt covered vegetation	(kWh/m^2)	0.493	5	0.099
Constructed Wetlands	>> De-silting of forebay & dispose sediments off site	(kWh/m^3)	17.346	5	3.469
Complex Rainwater Harvesting System	-				-
Water butts	-				-
Green Roof	-				-
Geocellular Systems	-				-

Table 2.6. Energy Factors for each drainage system. Source: Prepared by the authors.

From emission factor in kg CO_2e/unit, annual frequency of periodic maintenance activities and size, annual emissions can be calculated for each **activity** as follows:

$$E_{perio.maint.act.}\left(\frac{kg\ CO_2e}{year}\right) = EF_{perio.maint.act}\left(\frac{kg\ CO_2e}{unit}\right) \cdot Q_{perio.maint.act}(unit) \cdot f_{perio.maint.act.}\left(\frac{times}{year}\right) \quad \textit{Equation 2.25}$$

Where:

$E_{per.maint.act} = Annual\ \ emissions\ in\ a\ periodic\ maintenance$

$activity\left(\frac{kg\ CO_2e}{year}\right)$

$EF_{act.} = \ Emission\ factor\ of\ a\ periodic\ maintenance\ activity\left(\frac{kg\ CO_2e}{unit}\right)$

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

$f_{erio.maint.act.} = annual\ frecuency\ of\ a\ periodic\ maintenance\ activity\left(\frac{times}{year}\right)$

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

$$E_{perio.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kg\ CO_2e}{year}\right) = \sum E_{perio.maint.act.}\left(\frac{kg\ CO_2e}{year}\right) \quad \textit{Equation 2.26}$$

Where:

$E_{perio.maint.\ DRAINAGE\ SYSTEM} = Annual\ emissions\ in\ the\ periodic\ maintenance$

$of\ a\ drainage\ system\ \left(\frac{kg\ CO_2e}{year}\right)$

Annual energy consumption in the periodic maintenance of a drainage system is calculated from annual emissions and emission factor of the considered energy source:

$$EC_{perio.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kWh}{year}\right)=\frac{E_{perio.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kg\ CO_2e}{year}\right)}{EF_{ener.sour.}\left(\frac{kg\ CO_2e}{kWh}\right)}$$

Equation 2.27

Where:

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

$$EF_{ener.sour.} = Emission\ factor\ of\ the\ considered\ energy\ source\ \left(\frac{kg\ CO_2e}{kWh}\right)$$

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:

$$EC_{Maintenance\ DRAINAGE\ SYSTEM}\left(\frac{kWh}{year}\right) = EC_{ann.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kWh}{year}\right) + EC_{perio.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kWh}{year}\right)$$

Equation 2.28

Where:

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

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

$$E_{Maintenance\ DRAINAGE\ SYSTEM}\left(\frac{kg\ CO_2e}{year}\right) = E_{ann.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kg\ CO_2e}{year}\right) + E_{perio.maint.\ DRAINAGE\ SYSTEM}\left(\frac{kg\ CO_2e}{year}\right)$$

Equation 2.29

Where:

$$E_{Maintenance\ _{DRAINAGE\ SYSTEM}} = Annual\ emissions\ in\ the\ maintenance\ of\ a\ drainage\ system\ \left(\frac{kg\ CO_2e}{year}\right)$$

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 CO_2emissions 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 CO_2e)*: 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/m^2) 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/m^2) 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)

	Machinery	Materials	Total
Electricity	0%	77%	**77%**
Fuel	0%	23%	**23%**
Total	0%	100%	

Total Energy Consumption:
982 kWh
3,534 MJ

Emissions (kg CO_2e)

	Machinery	Materials	Total
Electricity	0%	81%	**81%**
Fuel	0%	19%	**19%**
Total	0%	100%	

Total Emissions:
322 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **245.42 kWh/m^3**

Coefficient for Emissions in Construction: **80.61 kgCO_2e/m^3**

Average Emission Factor: 0.33 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **2.01 kWh/m^3**

Coefficient for Emissions in Maintenance: **0.54 kCO_2e/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 m^3**

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	79%	**79%**
Fuel	0%	21%	**21%**
Total	0%	100%	

Total Energy Consumption:
121 kWh
436 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	83%	**83%**
Fuel	0%	17%	**17%**
Total	0%	100%	

Total Emissions:
40 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **242 kWh/m^3**

Coefficient for Emissions in Construction: **80 kgCO_2e/m^3**

Average Emission Factor: 0.33 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **16.01 kWh/m^3**

Coefficient for Emissions in Maintenance: **4.29 kCO_2e/m^3**

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 m^2** of green roof

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	43%	**43%**
Fuel	0%	57%	**57%**
Total	0%	100%	

Total Energy Consumption:
93 kWh
336 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	50%	**50%**
Fuel	0%	50%	**50%**
Total	0%	100%	

Total Emissions:
28 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **93 kWh/m^2**

Coefficient for Emissions in Construction: **28 kgCO_2e/m^2**

Average Emission Factor: 0.30 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **8.02 kWh/m^2**

Coefficient for Emissions in Maintenance: **2.14 kCO_2e/m^2**

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 m^2
- Type of permeable block paving system = total infiltration
- Outlet pipes required = No

- **Area** = **1 m^2** of permeable pavement

  Note: Area is referred to top area

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	62%	**62%**
Fuel	8%	30%	**38%**
Total	8%	92%	

Total Energy Consumption:
92 kWh
332 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	68%	**68%**
Fuel	7%	25%	**32%**
Total	7%	93%	

Total Emissions:
29 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **92 kWh/m^2**

Coefficient for Emissions in Construction: **29 $kgCO_2e/m^2$**

Average Emission Factor: 0.32 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **8.03 kWh/m^2**

Coefficient for Emissions in Maintenance: **2.14 kCO_2e/m^2**

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 m^2**
- **Volume = 9 m^3**

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

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	62%	**62%**
Fuel	8%	30%	**38%**
Total	8%	92%	

Total Energy Consumption:
92 kWh
332 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	68%	**68%**
Fuel	7%	25%	**32%**
Total	7%	93%	

Total Emissions:
29 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **92 kWh/m^3**

Coefficient for Emissions in Construction: **29 kgCO_2e/m^3**

Average Emission Factor: 0.32 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **6.39 kWh/m^3**

Coefficient for Emissions in Maintenance: **1.69 kCO_2e/m^3**

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 m^2**
- **Volume** = **9 m^3**

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

Energy Consumption (kWh)

	Machinery	Materials	Total
Electricity	0%	51%	**51%**
Fuel	20%	29%	**49%**
Total	20%	80%	

Total Energy Consumption:
502 kWh
1,806 MJ

Emissions (kg CO_2e)

	Machinery	Materials	Total
Electricity	0%	57%	**57%**
Fuel	18%	25%	**43%**
Total	18%	82%	

Total Emissions:
154 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **56 kWh/m^3**

Coefficient for Emissions in Construction: **17 kgCO_2e/m^3**

Average Emission Factor: 0.31 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **7.78 kWh/m^3**

Coefficient for Emissions in Maintenance: **2.05 kCO_2e/m^3**

2.4.7. Geocellular systems

Assumed design parameters:

Estimated parameters for 1 m^3 detention facility:

- Excavation: 1.3 m^3
- Liner to prevent infiltration (if detention system): 5 m^2
- Gate valves: 0,004
- Steel pipe: 0,02 m
- Pump: 0,5
- Modular Polypropylene Box: 45 kg

- **Volume = 1 m^3**

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	72%	**72%**
Fuel	3%	25%	**28%**
Total	3%	97%	

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

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	77%	**77%**
Fuel	2%	21%	**23%**
Total	2%	98%	

Total Emissions:
329 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **1012 kWh/unit**

Coefficient for Emissions in Construction: **329 kgCO_2e/unit**

Average Emission Factor: 0.32 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **8.02 kWh/unit**

Coefficient for Emissions in Maintenance: **2.14 kCO_2e/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 m^2**

Note: Area is referred to top area

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	52%	**52%**
Fuel	21%	27%	**48%**
Total	21%	79%	

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

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	59%	**59%**
Fuel	18%	23%	**41%**
Total	18%	82%	

Total Emissions:
8,464 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **137 kWh/m^2**

Coefficient for Emissions in Construction: **42 kgCO_2e/m^2**

Average Emission Factor: 0.31 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **0.34 kWh/m^2**

Coefficient for Emissions in Maintenance: **0.09 kCO_2e/m^2**

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 m^2**

Note: Area is referred to top area

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	48%	**48%**
Fuel	24%	28%	**52%**
Total	24%	76%	

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

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	54%	**54%**
Fuel	21%	25%	**46%**
Total	21%	79%	

Total Emissions:
1,152 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **118 kWh/m^2**

Coefficient for Emissions in Construction: **36 kgCO_2e/m^2**

Average Emission Factor: 0.30 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **1.60 kWh/m^2**

Coefficient for Emissions in Maintenance: **0.43 kCO_2e/m^2**

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 m^2**

Note: Area is referred to top area

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	33%	**33%**
Fuel	58%	9%	**67%**
Total	58%	42%	

Total Energy Consumption:
3,244 kWh
11,667 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	39%	**39%**
Fuel	53%	8%	**61%**
Total	53%	47%	

Total Emissions:
951 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **12 kWh/m^2**

Coefficient for Emissions in Construction: **3 kgCO_2e/m^2**

Average Emission Factor: 0.29 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **0.17 kWh/m^2**

Coefficient for Emissions in Maintenance: **0.05 kCO_2e/m^2**

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 m^2**
- **Volume = 9 m^3**

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

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	61%	**61%**
Fuel	11%	28%	**39%**
Total	11%	89%	

Total Energy Consumption:
912 kWh
3,281 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	67%	**67%**
Fuel	10%	23%	**33%**
Total	10%	90%	

Total Emissions:
288 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **101 kWh/m^3**

Coefficient for Emissions in Construction: **32 kgCO_2e/m^3**

Average Emission Factor: 0.32 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **7.78 kWh/m^3**

Coefficient for Emissions in Maintenance: **2.05 kCO_2e/m^3**

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 m^2**
- **Volume = 207 m^3**

Note: Area is referred to top area

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	58%	**58%**
Fuel	17%	25%	**42%**
Total	17%	83%	

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

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	64%	**64%**
Fuel	15%	21%	**36%**
Total	15%	85%	

Total Emissions:
8,271 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **43 kWh/m^2**

Coefficient for Emissions in Construction: **13 kgCO_2e/m^2**

Average Emission Factor: 0.31 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **0.22 kWh/m^2**

Coefficient for Emissions in Maintenance: **0.06 kCO_2e/m^2**

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 m^2**
- **Volume = 462 m^3**

Note:

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

Energy Consumption (kWh)

	Machinery	Materials	Total
Electricity	0%	5%	**5%**
Fuel	93%	1%	**95%**
Total	93%	7%	

Total Energy Consumption:
7,235 kWh
26,047 MJ

Emissions (kg CO_2e)

	Machinery	Materials	Total
Electricity	0%	7%	**7%**
Fuel	92%	1%	**93%**
Total	92%	8%	

Total Emissions:
1,962 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **16 kWh/m^3**

Coefficient for Emissions in Construction: **4 kgCO_2e/m^3**

Average Emission Factor: 0.27 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **0.02 kWh/m^3**

Coefficient for Emissions in Maintenance: **0.01 kCO_2e/m^3**

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**

Note:

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

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	34%	**34%**
Fuel	57%	9%	**66%**
Total	57%	43%	

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

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	40%	**40%**
Fuel	52%	8%	**60%**
Total	52%	48%	

Total Emissions:
3,466 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **26 kWh/m^3**

Coefficient for Emissions in Construction: **7,5 kgCO_2e/m^3**

Average Emission Factor: 0.29 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **0.02 kWh/m^3**

Coefficient for Emissions in Maintenance: **0.01 kCO_2e/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 m^2**
- **Volume = 286 m^3**

Note:

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

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	43%	**43%**
Fuel	45%	12%	**57%**
Total	45%	55%	

Total Energy Consumption:
10,574 kWh
38,067 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	40%	**40%**
Fuel	52%	8%	**60%**
Total	52%	48%	

Total Emissions:
3,187 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **37 kWh/m^3**

Coefficient for Emissions in Construction: **11 kgCO_2e/m^3**

Average Emission Factor: 0.30 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **0.03 kWh/m^3**

Coefficient for Emissions in Maintenance: **0.01 kCO_2e/m^3**

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 m^2**

Note:

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

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	42%	**42%**
Fuel	46%	11%	**58%**
Total	46%	54%	

Total Energy Consumption:
10,277 kWh
36,998 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	49%	**49%**
Fuel	41%	10%	**51%**
Total	41%	59%	

Total Emissions:
3,092 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **72 kWh/m^2**

Coefficient for Emissions in Construction: **11 kgCO_2e/m^2**

Average Emission Factor: 0.30 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **0.07 kWh/m^2**

Coefficient for Emissions in Maintenance: **0.02 kCO_2e/m^2**

Regarding ***Conventional Drainage***, the following systems have been analyzed:

2.4.17. Sewer pipes

Assumed design parameters:

- Conventional drainage network
- **Pipe Lengh: 900 m**

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	36%	**36%**
Fuel	43%	21%	**64%**
Total	43%	57%	

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

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	42%	**42%**
Fuel	38%	19%	**58%**
Total	38%	62%	

Total Emissions:
9,000 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **32 kWh/m**

Coefficient for Emissions in Construction: **10 kgCO_2e/m**

Average Emission Factor: 0.30 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **4.01 kWh/m^3**

Coefficient for Emissions in Maintenance: **1.07 kCO_2e/m^3**

2.4.18. Standard pavement

Assumed design parameters:

- Conventional standard pavement
- **Area** = **1 m^2** of pavement
  Note: Area is referred to top area

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	62%	**62%**
Fuel	2%	36%	**38%**
Total	2%	98%	

Total Energy Consumption:
164 kWh
590 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	68%	**68%**
Fuel	1%	31%	**32%**
Total	1%	99%	

Total Emissions:
52 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **164 kWh/m^2**

Coefficient for Emissions in Construction: **52 $kgCO_2e/m^2$**

Average Emission Factor: 0.32 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **4.01 kWh/m^2**

Coefficient for Emissions in Maintenance: **1.07 kCO_2e/m^2**

2.4.20. Structural detention facilities

Assumed design parameters:

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

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	62%	**62%**
Fuel	5%	32%	**38%**
Total	5%	95%	

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

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	68%	**68%**
Fuel	4%	27%	**32%**
Total	4%	96%	

Total Emissions:
3,466 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **849 kWh/m^3**

Coefficient for Emissions in Construction: **269 kgCO_2e/m^3**

Average Emission Factor: 0.32 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **8.02 kWh/m^3**

Coefficient for Emissions in Maintenance: **2.14 kCO_2e/m^3**

2.4.21. Conventional roof

Assumed design parameters:

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

Energy Consumption (kWh)

	Machinery	Materials	**Total**
Electricity	0%	46%	**46%**
Fuel	0%	54%	**54%**
Total	0%	100%	

Total Energy Consumption:
123 kWh
443 MJ

Emissions (kg CO_2e)

	Machinery	Materials	**Total**
Electricity	0%	52%	**52%**
Fuel	0%	48%	**48%**
Total	0%	100%	

Total Emissions:
37 kg CO_2e

Construction

Coefficient for Energy Consumption in Construction: **123 kWh/m^2**

Coefficient for Emissions in Construction: **37 kgCO_2e/m^2**

Average Emission Factor: 0.30 kg CO_2e/kWh

Maintenance

Coefficient for Energy Consumption in Maintenance: **4.01 kWh/m^2**

Coefficient for Emissions in Maintenance: **1.07 kCO_2e/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).

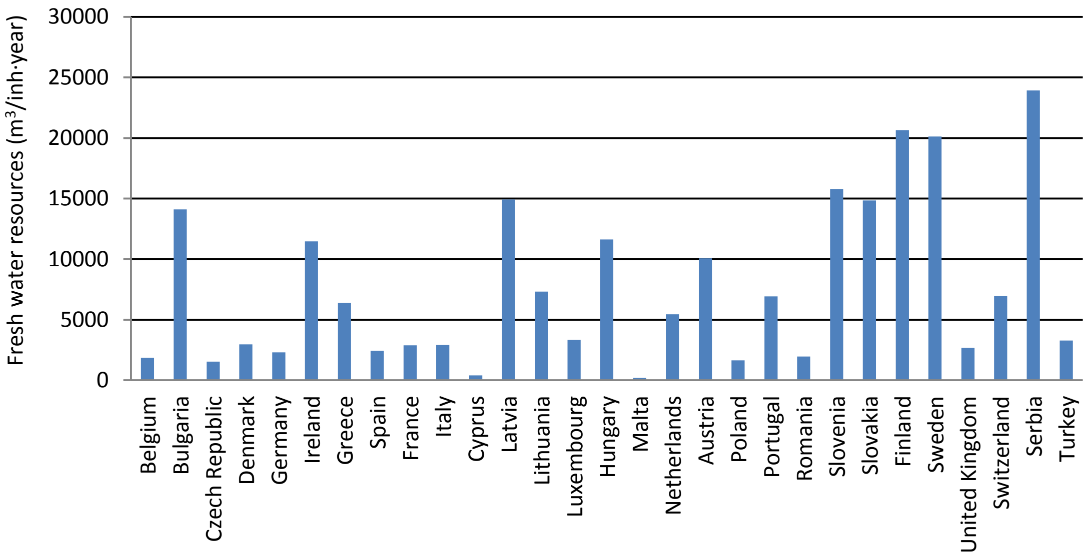

Figure 3.1. Long Term Average Annual Fresh Water Resources for some European Countries
(EUROSTAT, 2013)

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.

	TOTAL FRESH WATER ABSTRACTION *(m³/inh·year)*	Fresh surface water abstraction *(m³/inh·year)*	Fresh ground water abstraction *(m³/inh·year)*	Fresh surface water abstraction *(%)*	Fresh ground water abstraction *(%)*
Belgium	70	24	46	34	66
Bulgaria	132	70	62	53	47
Czech Republic	70	38	33	54	46
Denmark	76	1	76	1	99
Germany	64	18	46	28	72
Estonia	44	23	21	53	47
Ireland	148	110	39	74	26
Greece	77	56	21	73	27
Spain	132	98	34	74	26

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

Table 3.1. Average Annual (2002-2009) Fresh Water Abstraction by public water supply for some European countries (m3/inh·year) (EUROSTAT, 2013)

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).

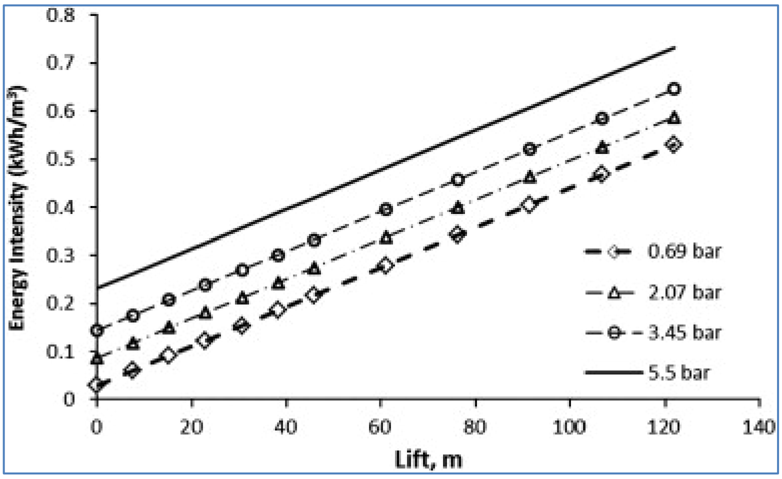

Figure 3.2. Electricity required for pumping 1 m^3 of water (Martin DL, 2011)

State, Country	Unit Value (kWh/m^3)	Lift (m)	Reference
California, USA	0,14 – 0,69	36-98	(GEI/Navigant, 2010)
Ontario, Canada	0,25–3,02	-	(Maas, 2010; Maas, 2009)

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.

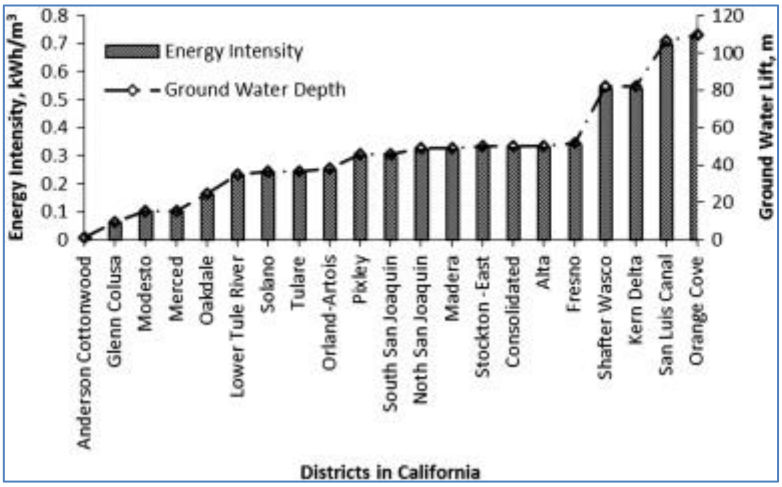

Figure 3.3. Ground water pumping energy values across California (C. Burt, 2008)

3.2. Surface Water pumping

Surface water pumping refers to pumping system 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.

Location	Length, Lift (km); (m)	Energy (kWh/m^3)	Unit Value (kW h/m^3 km)	Reference
West Branch Aqueduct, CA (USA)	(502);(-)	2,07	0,004	(GEI/Navigant, 2010)
Coastal Branch Aqueduct, CA (USA)	(457);(-)	2.31	0,005	(Dale, 2004)and (Anderson, 2006)
Transfer From Colorado River to Los Angeles, CA	(389);(-)	1.6	0.004	(Wilkinson, 2000)
Shoalhaven River, Australia	(-); (600)	2,4		(Anderson, 2006)
Water Pipe, Australia	(450);(-)	3.3	0.007	(Stokes J., 2009) and (Scott C., 2009)
SSDP to PIWSS, Australia [1]	(116);(-)	0.21	0.002	(Scott C., 2009)and (AG-DSEWPC, 2010)
PSDP to PIWSS, Australia[2]	11.2	0,055	0,005	(Scott C., 2009), (AG-DSEWPC, 2010)

[1] *Southern Seawater Desalination Plant, Perth (SSDP). Perth Integrated water supply system (PIWSS).*

Tortosa to Aguadulce, (Spain)	(745), (-)	4.07	0,005	(Raluy R.G, 2005)and (Muñoz I., 2010)

Table 3.3. Energy Requirements for Ground Water Pumping.

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.

$$EC_{pumping}\,(kWh) = f(l, Q, p, f_l)$$

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_{hydr}) refers to the power which is transferred by the pump´s shaft to the water. Three different water pumping needs can be distinguished:

- ΔH: due to height difference.
- ΔP: 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_{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_{mec}) refers to the power transferred from the motor to the shaft of the pump. It depends on the efficiency of the pump (η_{mec}=mechanical efficiency).

And finally, **Supply power (P_{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 (η_{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:

$$ENE_i = (\Delta H_i + \Delta P_i + Psup_i) \cdot \rho_{water} \cdot g \cdot \frac{1}{3600} \cdot \frac{1}{1000} \cdot \frac{100}{\eta_{mec}} \cdot \frac{100}{\eta_{ener}}$$

Equation 3.1

Where:

$i = pipeline\ section\ which\ connects\ two\ points$

$ENE_i = Energy\ consumed\ in\ pumping\ i\ (kWh/m^3)$

$\Delta H_i = Height\ difference\ (mwc)$

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

$Psup_i = Supplied\ Pressure\ need\ for\ the\ final\ consumer\ (mwc).$

$\rho_{water} = Density\ of\ water\ \left(1000\ \frac{kg}{m^3}\right)$

$g = Gravity\ \left(9.81\ \frac{m}{s^2}\right)$

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

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

3.3.1. Height difference - ΔH

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 - ΔP

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:

$f = Darcy - Weisbach\ \ friction\, factor$

$D = Internal\ diameter\ of\ the\ pipe\ (mm)$

$L = Pipe\ lenght\ (m)$

$v = average\ water\ velocity\ (m/s)$

$\%_{LOC}\ = percentage\ of\ the\ friction\ losses\ (\%)$

The friction factor *f* is estimated with the Colebrook White´s equation for turbulent flow:

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

Equation 3.3

Where:

$R_e\ = (\ v)\ /\ \vartheta \bullet (\ D)\ /\ 1000 = Reynolds\ Number$

Where: $\vartheta = Kinematic\ water\ viscosity\ (10^{-6}\ m^2/s)$

$k\ = roughness\ of\ duct, pipe\ or\ tube\ surface\ (mm)$

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:

$$ENE_{Total} = \sum_i (\Delta H_i + \Delta P_i + Psup_i) \cdot \rho_{water} \cdot g \cdot \frac{1}{3600} \cdot \frac{1}{1000} \cdot \frac{100}{\eta_{mec}} \cdot \frac{100}{\eta_{ener}} \quad \text{Equation 3.4}$$

Where:

$i = pipeline\ section\ which\ connects\ two\ points$

$ENE_{Total} = Total\ Energy\ consumed\ due\ \ pumping\ i\ (kWh/m^3)$

$\Delta H_i = Height\ difference\ (mwc)$

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

$Psup_i = Supplied\ Pressure\ need\ for\ the\ final\ consumer\ (mwc).$

$\rho_{water} = Density\ of\ water\ \left(1000\ \frac{kg}{m^3}\right)$

$g = Gravity\ \left(9.81\ \frac{m}{s^2}\right)$

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

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

Total emissions due to **water pumping** are calculated as follows:

$$EMI_{Total} = \sum_i ENE_i \cdot EF_i \quad \text{Equation 3.5}$$

Where:

$EMI_{Total} = Total\ emissions\ due\ to\ pumping\ \left(\frac{kg\ CO_2 e}{m^3}\right)$

$ENE_i = Energy\ consumed\ in\ pumping\ i\ \left(\frac{kWh}{m^3}\right)$

$EF_i = Emission\ factor\ for\ fuel\ or\ electricity \left(\frac{kg\ CO_2 e}{kWh}\right)$

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.

Item/Plant Production	Treatment Plant Size (m^3/day)					
	3785	*18925*	*37850*	*75700*	*189250*	*378500*
	Electricity consumption (kWh/day)					
Rapid Mixing	41	176	308	616	1540	3080
Flocculation	10	51	90	181	452	904
Sedimentation	14	44	88	175	438	876
Alum Feed System	9	10	10	20	40	80
Polymer Feed System	47	47	47	47	47	47
Lime Feed System	9	11	12	13	15	16
Filter Surface Wash Pumps	8	40	77	153	383	767
Backwash Water Pumps	13	62	123	246	657	1288
Residuals Pumping	4	20	40	80	200	400
Thickened Solids Pumping	N/A	N/A	N/A	123	308	616
Chlorination*	2	2	2	2	4	8
General UV Irradiation (1)*	114	568	1136	2271	5678	11355
Ozone (1)*	341	1703	3407	6813	17033	34065

**Disinfection processes: Chlorination is the widest disinfection treatment, UV Irradiation and Ozonataion 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 c**omplete DWTPs**, which include all the processes shown in the table plus different disinfection processes (**Chlorination, UV Irradiation or Ozonation**).

Treatment Plant Size (m^3/day)	3785	18925	37850	75700	189250	378500	Average
Total Electricity consumption for Basic Treatment (kWh/day)	26	97	180	358	894	1788	
Total Electricity consumption for Basic Treatment (kWh/m^3)	0.0069	0.0051	0.0048	0.0047	0.0047	0.0047	**0,0052**
Total Electricity consumption for Complete Treatment with Chlorination (kWh/day)	157	463	797	1656	4084	8082	
Total Electricity consumption for Complete Treatment with Chlorination (kWh/m^3)	0.041	0.024	0.021	0.022	0.022	0.021	**0,0253**
Total Electricity consumption for Complete Treatment with UV radiation (kWh/day)	271	1031	1933	3927	9762	19437	
Total Electricity consumption for Complete Treatment with UV Radiation (kWh/m^3)	0.071	0.054	0.051	0.052	0.052	0.051	**0,0553**
Total Electricity consumption for Complete Treatment with Ozonation (kWh/day)	498	2166	4204	8469	21117	42147	
Total Electricity consumption for Complete Treatment with Ozonation (kWh/m^3)	0.131	0.114	0.111	0.112	0.112	0.111	**0,1153**

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).

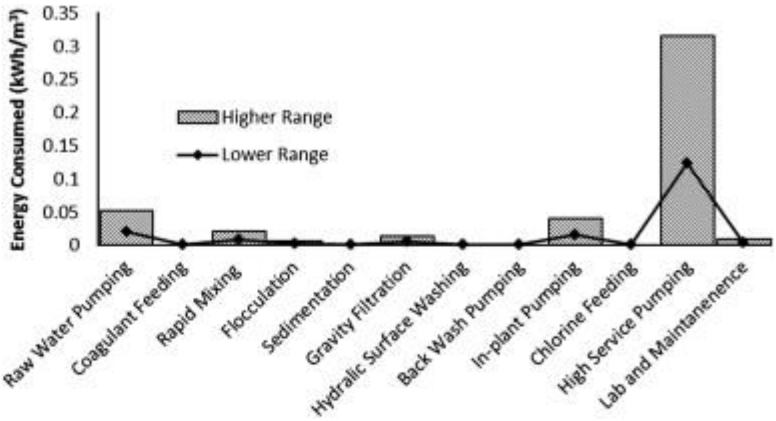

Figure 4.1. Energy consumption of unit processes in surface water treatment plants in United States (WEF, 2010)

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 m3/d) (Maas, 2009).

Country	Energy Needs	Reference
Australia	0,01–0,2	(Cammerman, 2009)
Taiwan	0,16–0,25	(Cheng, 2002)
USA	0,184–0,47	(WEF, 2010)
Canada	0,38–1,44	(Maas, 2010)
Spain	0,11–1,5	(Muñoz I., 2010)
New Zealand	0,15–0,44	(Kneppers B, 2009)

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:

	Treatment Plant Size (m^3/day)			
	3785	*18925*	*37850*	*75700*
Processes	**Electricity consumption (kWh/day)**			
Chlorination	9	45	93	186
General UV Irradiation	76	379	757	1514
Ozone	114	568	1136	2271
Processes	**Electricity consumption (kWh/m^3)**			
Chlorination	0.0024	0.0024	0.0025	0.0025
General UV Irradiation (1)	0.02	0.02	0.02	0.02
Ozone (1)	0.03	0.03	0.03	0.03

Table 4.4. Electricity consumption for different disinfecting processes and plant sizes (kWh/m^3)

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.

Technology	Plant Capacity (m^3/day)	Thermal Energy (kWh/m^3)	Electrical Energy (kWh/m^3)	Operation Temperature (°C)
MSF	4000-450000	55-220	4-6	90-112
MED	100-56000	40-220	1.5-2.5	50-70
MVC	5-17000	-	6-12	50-70
RO	0.01-360000	-	2.8-12	<40

Table 4.5. Energy consumption in Desalination Technologies (kWh/m^3). (IDA, 2012)

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 (kgCO_2e/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 m^3/day, average unit energy consumptions in kWh/m^3 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:

$$EC_{DWTP_i}\left(\frac{kWh}{year}\right) = Capacity_{DWTP_i}\left(\frac{m^3}{day}\right) \cdot UEC_{DWTP_i}\left(\frac{kWh}{m^3}\right) \cdot \frac{365\ days}{1\ year} \qquad \textit{Equation 4.1}$$

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:

$$EC_{DWP}\left(\frac{kWh}{year}\right) = \sum\left(EC_{DWTP_i}\left(\frac{kWh}{year}\right) \cdot US_i(\%)\right) \qquad \textit{Equation 4.2}$$

Where:

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

$$EC_{DWP} = annual\ energy\ consumption\ in\ water\ production \left(\frac{kWh}{year}\right)$$

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

$$US_i = Utilization\ share\ of\ each\ treatment\ plant = share\ of\ each\ water\ source\ (\%)$$

Finally, **annual emissions from a DWTP Plant** are calculated as shown below:

$$E_{\ DWTP} \left(\frac{kg\ CO_2e}{year}\right) = EC_{DWP} \left(\frac{kWh}{year}\right) \cdot EF_{elec.count.} \left(\frac{kg\ CO_2e}{kWh}\right) \quad \textit{Equation 4.3}$$

Where:

$$E_{\ DWTP} = annual\ energy\ emissions\ in\ the\ drinking\ water\ production \left(\frac{kg\ CO_2e}{year}\right)$$

$$EC_{DWP} = annual\ energy\ consumption\ in\ the\ water\ production \left(\frac{kWh}{year}\right)$$

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

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/m^3, and concretely California shows an estimated energy consumption in influent waste water pumping and collection in the range from 0.003 to 0 0.04 kWh/m^3 [(CEC, 2006). (GEI/Navigant, 2009)]. In New Zealand waste water pumping ranges from 0.04 to 0.19 kWh/m^3, while Canada estimates its energy consumption from 0.02 to 0.1 kWh/m^3 [(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/m^3 (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/m^3 (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/m^3 (Toffey, 2010). The average consumption of mixing and pumping action at this stage for a 1.000 m^3 sewage plant is in the range of 0.012 – 0.033 kWh/ m^3 (Tassou, 1988). Organic impurities are acted upon by heterotrophic microorganisms presented 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 1.0 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 m^3 of water [(Murty BS, 2011). (Toffey, 2010)]. An energy intensity of 0.055 kWh/m^3 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/m^3 (Radcliffe, 2004).

In China, aeration systems like wetlands and land treatment had an average energy consumption of 0.253 kWh/m^3 while aeration processes in the UK were reported to consume an average of 0.13 kWh/m^3 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 bio-film 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.

Treatment	Australia	China	USA	Japan	Reference
Lagoons		0.253 (avg)	0.09 - 0.29		(Yang L, 2010). (Quantum Consulting, 2001)
Activated sludge	0.1 (avg)	0.269 (avg)	0.33 – 0.6	0.30 -1.89	(WEF, 2010). (Yang L, 2010)]. (Mizuta K, 2010).
Oxidation ditch	0.5 – 1.0	0.302		0.43 – 2.07	(Yang L, 2010)]. (Mizuta K, 2010)
Membrane bio-reactor	0.10 – 0.82	0.33 (avg)	0.8 – 0.9; 0.49 – 1.5		(WEF, 2010)]. (Yang L, 2010). (Lesjean B, 2011).
Trickling filter			0.18 – 0.42		(Quantum Consulting, 2001). (EPA, 2008)].
Advanced Wastewater treatment			0.31 – 0.40		(Quantum Consulting, 2001). (EPA, 2008) (Metcalf L, 1979).

Table 5.1. Energy intensity of secondary waste water treatment (kWh/m^3)

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/m^3 (Stillwell AS, 2010)]. Anaerobic digestion has the capacity to deliver gas at the rate 35 m^3/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/m^3 (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 trans-membrane 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/m^3 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/m^3 (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/m^3 (Quantum Consulting, 2001).

5.4. WASTEWATER TREATMENT ENERGY CONSUMPTION CALCULATION METHOD

Annual energy consumption (kWh/year) and emissions (kgCO_2e/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 kgCO_2/m^3 should be also considered.

Treatment Plant Size categories (m^3/day)			Unit Electricity Consumption (kWh/m^3)			
	Only Primary Treatment	Aerated basins	Trickling Filter	Activated Sludge *with* nutrients removal	Activated Sludge *without* nutrients removal	Advanced wastewater treatment with nitrification
x ≤ 3785	0.01	0.02	0.48	0.59	0.59	0.78
3785 < x ≤ 18925	0.01	0.02	0.26	0.36	0.36	0.51
18925 < x ≤ 37850	0.01	0.02	0.23	0.32	0.32	0.47
37850 < x ≤ 75700	0.01	0.02	0.20	0.29	0.29	0.44
75700 < x ≤ 189250	0.01	0.02	0.18	0.28	0.28	0.42
X > 189250	0.01	0.02	0.18	0.27	0.27	0.41

Table 5.2. Unit Electricity Consumption for Wastewater Treatment by Size categories of Plant

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:

$$Capacity_{\ WWTP}\ \ (PE) = BOD_5\left(\frac{1000\ kg\ O_2}{day}\right)\cdot\frac{1\ PE}{0.06\ \frac{kg\ O_2}{day}}$$

Equation 5.1

Where:

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

$BOD_5 = five\ day\ biochemical\ oxygen\ demand\left(\frac{1000\ kg\ O_2}{day}\right)$

$Acoording\ to\ Diretive\ 91/271/EEC{:}\ 1\ \ P.E \rightarrow\ BOD_5 = 60\frac{gO_2}{day}$

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

$$Capacity_{\ WWTP}\ \left(\frac{m^3}{day}\right) = Capacity_{\ WWTP}\ \ (PE)\cdot WW\ Influent\ \left(\frac{m^3}{PE\cdot day}\right)$$

Equation 5.2

Where:

$$Capacity_{\ WWTP} = Waste\ water\ treatment\ plant\ capacity\ \left(\frac{m^3}{day}\ or\ PE\right)$$

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

Once WWTP capacity is expressed as *m^3/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:

$$EC_{\ WWTP}\ \left(\frac{kWh}{year}\right) = Capacity_{\ WWTP}\ \left(\frac{m^3}{day}\right)\cdot UEC_{\ WWTP}\left(\frac{kWh}{m^3}\right)\cdot\frac{365\ days}{1\ year}$$

Equation 5.3

Where:

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

$$Capacity_{\ WWTP} = Wastewater\ treatment\ plant\ capacity\ \left(\frac{m^3}{day}\right)$$

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

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

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

Equation 5.4

Where:

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

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

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

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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/m^2 in 2009, with a large gap between residential (around 200 kWh/m^2) and non-residential buildings (around 300 kWh/m^2) (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 m^2 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).

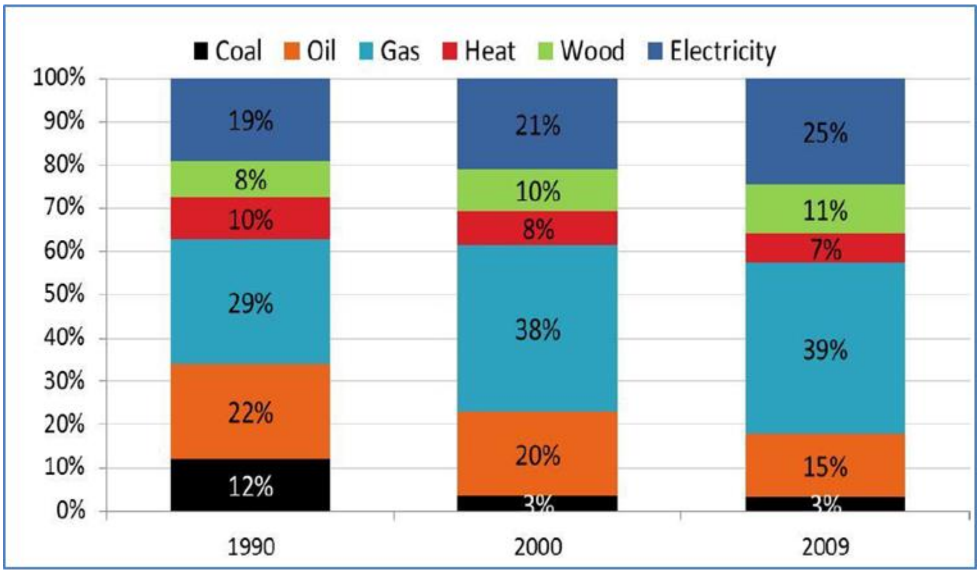

Figure 6.1. Household energy consumption by energy source in EU.

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.

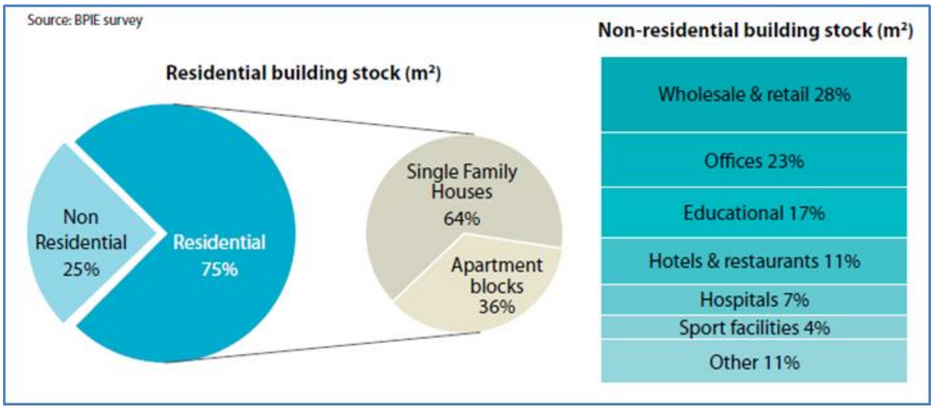

Figure 6.2. Energy consumption by building categories in Europe.

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.

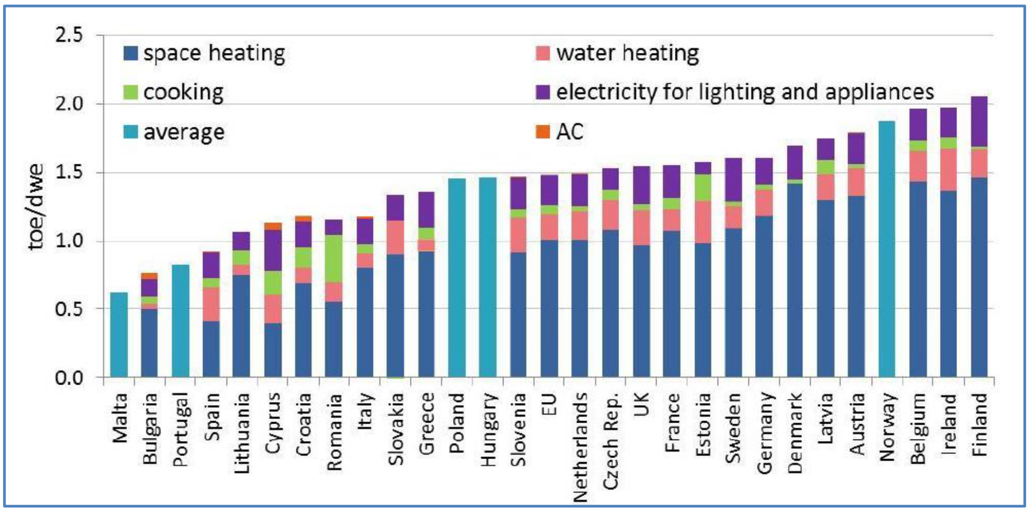

Figure 6.3. Household energy consumption by end-use for EU-countries (ADEME, 2012)

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.

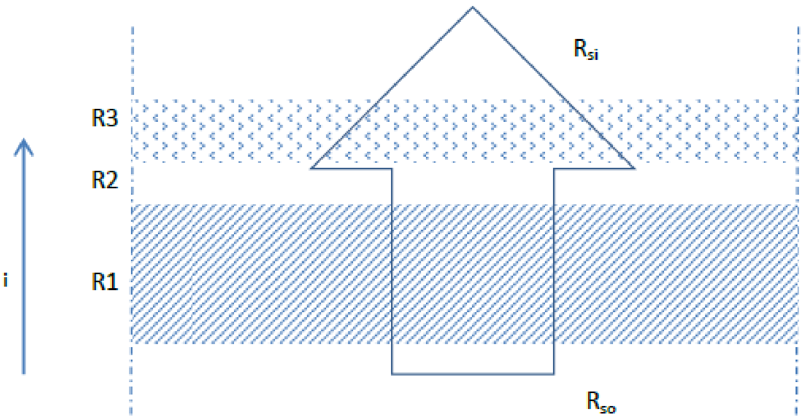

Figure 6.4. One-dimensional model of heat flux (M.I DÍAZ, 2005)

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/m^2·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:

$$R_{SI}\left(\frac{m^2\cdot K}{W}\right) = thermal\ resitance\ of\ internal\ surface\ (outside\ air)$$

$$R_{SO}\left(\frac{m^2\cdot K}{W}\right) = thermal\ resitance\ of\ outside\ surface\ (indoor\ air)$$

$$R_{i}\left(\frac{m^2\cdot K}{W}\right) = thermal\ resitances\ of\ layers\ which\ compounds\ the\ element$$

Thermal resistance, $\boldsymbol{R_i}$ of a thermally homogeneous layer is defined as follows:

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

Equation 6.2

Where:

$$t = layer\ thickness\ (m)$$

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

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:

Material	Thermal conductivity W/(m·K)
XPS (Extruded Polystyrene) Insulation	0.04–0.14*[a]
Polyethylene	0.33 -0.52*[a]
Air	0.025[a]
Concrete	0.1-1.8*[a]

* Values depend on density. generally increasing with increasing density.
[a] (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:

$$Q\ (W) = U\cdot A\cdot \Delta T$$

Equation 6.3

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

Equation 6.4

Where:

$Q = heat\ losses\ through\ the\ element\ (W)$

$U = overall\ heat\ transfer\ coefficient\ \left(\frac{W}{m^2 \cdot K}\right)$

$A = element\ area\ (m^2)$

$\Delta T = difference\ between\ outside\ and\ inside\ temperature\ in\ the\ building\ (K)$

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)."

6.3. Building insulation. Energy performance of a green roof

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 CO_2 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.

Country	Source	U-value (W/m^2) 2000-2008
Austria	MonMech2013	0.22
Belgium	TABULA	0.57
Bulgaria	BPIE	0.30
Cyprus	CY-STAT	0.55
Czech Rep.	BPIE. TABULA. panel SCAN 2009	0.24
Denmark	BPIE. TABULA	0.14
Estonia	TABULA. BPIE	0.18
Finland	BPIE	0.18
France	BPIE. TABULA	0.22
Germany	IWU	0.22
Greece	RES-H	0.39
Hungary	BPIE	0.25
Ireland	CSO 2011	0.31
Italy	BPIE.TABULA	1.20
Latvia		n.a.
Lithuania	RES-H.State Enterprise Centre of Registers	0.18
Luxembourg	BPIE	0.25
Malta	ODYSSEE.BPIE. NSO. TABULA	1.81
Netherlands	RES-H	0.40
Poland	BPIE. TABULA	0.60
Portugal	BPIE	1.33
Romania	BPIE	1.00
Slovakia	BPIE.Slovak building standards	0.30
Slovenia	TABULA.BPIE	0.20
Spain	TABULA. ODYSSEE	0.54
Sweden		n.a.
UK		n.a.
Serbia	RS-STAT	0.45
Croatia	HR stat	0.29

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.

Ref.	Description*	U-Value (Q/m^{2}K)	% Change**
1	NTK Building - bare roof	2,433	
	NTK Building - green roof 100 mm soil & short plants	1,772	-27,2
	NTK Building - green roof 150 mm soil & taller plants	1,646	-32,4
2a	APB Centre, 4/F - bare roof	1,228	
	APB Centre, 4/F - green roof 100 mm soil & sedum plants	1,020	-16,9
2b	APB Centre, 10/F - bare roof	1,194	
	APB Centre, 10/F - green roof 100 mm soil & sedum plants	0,997	-16,5

3	YLGPS - bare roof	2,166	
	YLGPS - green roof, pavement area, 92 mm soil & grass	1,701	-21,5
	YLGPS - green roof, planter area 350 mm soil & tall plants	1,248	-42,4
4	SBCPS - bare roof	2,830	
	SBCPS - green roof (very light weight) 50 mm soil	2,069	-26,9

Note: * Building roof is included in the calculation of U-values for different types of green roofs
** % Change = percentage change of U-value as compared to the respective bare roof

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-bitumious 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).

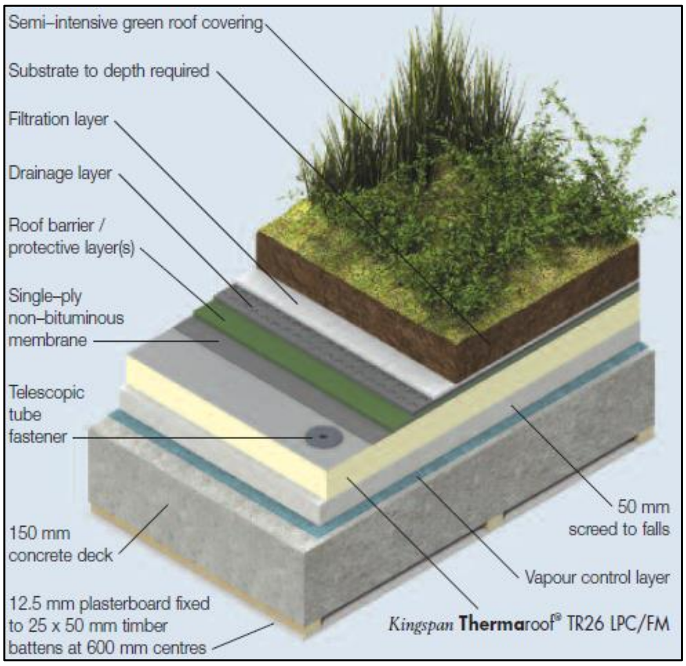

Figure 6.5. Semi-Intensive Green Roof Covering-Dense Concrete Deck (KINGSPAN, 2011)

U-value varies with insulant thickness:

Insulant Thickness (mm)	U-values (W/m^2·K)
75	0,25
80	0,24
90	0,22
100	0,2
105	0,19
110	0,18
115	0,17
120	0,17
125	0,16
130	0,16
135	0,15
140	0,14
150	0,14
75+80*	0,13
80+85*	0,12
90+90	0,11
100+100	0,10

** 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)

6.4. Calculation Method for Energy Savings in Buildings: Greenroof

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:

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

Equation 6.5

Where:

PS_{GR+CR} $= unitary\ power\ savings\ by\ installing\ a\ greenroof\ over\ a\ conventioanl\ roof\ \left(\frac{W}{m^2}\right)$

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

$\Delta T = difference\ between\ outside\ and\ inside\ temperature\ in\ the\ building\ (K)$

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:

$$PS_{GR+CR}\ \left(\frac{W}{m^2}\right) = \Delta U \left(\frac{W}{m^2 \cdot K}\right) \cdot \Delta T\ (K)\ \cdot \frac{1}{\eta_{HVAC}}$$ *Equation 6.6*

Where:

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

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

$\Delta T = difference\ between\ outside\ and\ inside\ temperature\ in\ the\ building\ (K)$

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 ΔT 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 ΔT and energy savings can be obtained and U-value for the green roof can be calculated.

- Indoors temperature: to simplify calculations of ΔT, 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:

$$ENS_{ij}\left(\frac{Wh}{m^2}\right) = \Delta U\left(\frac{W}{m^2 \cdot K}\right) \cdot \Delta T\ (K) \cdot \frac{1}{\eta_{HVAC_{winter}}} =$$
$$= \Delta U \cdot \left(T_{winter\ setpoint} - T_{outdoors_{ij}}\right) \cdot \frac{1}{\eta_{Boiler}} \cdot \frac{use\ share_{Boiler}}{100} + \Delta U \cdot \left(T_{winter\ setpoint} - T_{outdoors_{ij}}\right) \cdot \frac{1}{\eta_{Heat\ pump}} \cdot \frac{use\ share_{Heat\ pump}}{100}$$

Equation 6.7

Where:

$i = hour$ (0 h… 23 h)

$j = winter\ month$ (November… April)

$ENS_{ij} = average\ unitary\ energy\ savings\ during\ the\ hour\ i\ of\ a\ representative$

$day\ of\ the\ winter\ month\ j\ \left(\frac{Wh}{m^2}\right)$

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

$\Delta T = difference\ between\ outside\ and\ inside\ temperature\ in\ the\ building\ (K)$

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

$T_{outdoors_{ij}} = average\ temperature\ outside\ the\ buiding\ during\ the\ hour\ i\ of\ a\ represetative\ day$

$of\ the\ \ the\ winter\ month\ j\ (K)$

$\eta_{HVAC_{winter}} = eficciency\ of\ the\ HVAC\ system\ \ in\ winter \approx \eta_{Boiler} = \ boiler\ efficiency\ or\ \eta_{Heat\ Pump} = Heat\ Pump\ efficiency$

$use\ share_{Boiler}$ *= use share of the boiler in winter (%)*

$use\ share_{Heat\ Pump}$ *= 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:

$$ENS_j\left(\frac{Wh}{m^2 \cdot day}\right) = \sum ENS_{ij}\left(\frac{Wh}{m^2}\right)$$

Equation 6.8

Where:

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

ENS_{ij} $= average\ unitary\ energy\ savings\ during\ the\ hour\ i\ of\ a\ representative$

$day\ of\ the\ winter\ month\ j\ \left(\frac{Wh}{m^2}\right)$

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

$$ENS_{winter}\left(\frac{kWh}{m^2}\right) = \frac{\sum\left(ENS_j\left(\frac{Wh}{m^2\cdot day}\right)\cdot N_{working\ days_j}(day)\right)}{1000} \qquad \textit{Equation 6.9}$$

Where:

$j = winter\ months$

$ENS_{winter} = average\ unitary\ energy\ savings\ during\ the\ winter\ \left(\frac{kWh}{m^2}\right)$

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

$N_{working\ days_j} = number\ of\ working\ days\ in\ the\ winter\ month\ j\ (days)$

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:

$$ES_{ij}\left(\frac{kg\ CO_2e}{m^2}\right) =$$
$$= \Delta U\cdot\left(T_{winter\ setpoint} - T_{outdoors_{ij}}\right)\cdot\frac{1}{\eta_{Boiler}}\cdot\frac{use\ share_{Boiler}}{100}\cdot EF_{fuel} + \Delta U$$
$$\cdot\left(T_{winter\ setpoint} - T_{outdoors_{ij}}\right)\cdot\frac{1}{\eta_{Heat\ pump}}\cdot\frac{use\ share_{Heat\ pump}}{100}$$
$$\cdot EF_{elec.count.} \qquad \textit{Equation 6.10}$$

Where:

$i = hour$ (0 h… 23 h)

$j = winter\ month$ (November… April)

$ES_{ij} = average\ unitary\ emissions\ savings\ during\ the\ hour\ i\ of\ a\ representative\ day$

$of\ the\ winter\ month\ j\ \left(\frac{kg\ CO_2e}{m^2}\right)$

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

$EF_{fuel} = Fuel\ Emission\ factor \left(\frac{kg\ CO_2e}{kWh}\right)$

Average **emissions savings** per m^2 of green roof during a representative **day** of a winter month can be calculated as follows:

$$ES_j \left(\frac{kg\ CO_2e}{m^2 \cdot day}\right) = \sum ES_{ij} \left(\frac{kg\ CO_2e}{m^2}\right) \qquad \textit{Equation 6.11}$$

Where:

$ES_j = average\ emissions\ savings\ during\ one\ representative\ day\ of\ the\ winter\ month\ j \left(\frac{kg\ CO_2e}{m^2}\right)$

$ES_{ij} = average\ unitary\ emissions\ savings\ during\ the\ hour\ i\ of\ a\ representative\ day$

$of\ the\ winter\ month\ j \left(\frac{kg\ CO_2e}{m^2}\right)$

Average **emissions savings** per m^2 of greenroof during the **winter** can be calculated as follows:

$$ES_{winter} \left(\frac{kg\ CO_2e}{m^2}\right) = \frac{\sum \left(ES_j \left(\frac{kg\ CO_2e}{m^2 \cdot day}\right) \cdot N_{working\ days_j}(day)\right)}{1000} \qquad \textit{Equation 6.12}$$

Where:

$j = winter\ months$

$ES_{winter} = average\ unitary\ emissions\ savings\ during\ the\ winter \left(\frac{kg\ CO_2e}{m^2}\right)$

$ES_j = average\ emissions\ savings\ during\ one\ representative\ day\ of\ the\ winter\ month\ j \left(\frac{kg\ CO_2e}{m^2}\right)$

$N_{working\ days_j} = number\ of\ working\ days\ in\ the\ winter\ month\ j\ (days)$

6.4.2. Summer

Similar process can be used to calculate the average energy savings per m^2 of green roof during the summer.

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

$$ENS_{ij}\left(\frac{Wh}{m^2}\right) = \Delta U\left(\frac{W}{m^2 \cdot K}\right) \cdot \Delta T\ (K)\ \cdot \frac{1}{\eta_{HVAC\,summer}} =$$
$$= \Delta U \cdot \left(T_{outdoors\,ij} - T_{summer\ setpoint}\right) \cdot \frac{1}{\eta_{Heat\ Pump}}$$

Equation 6.13

Where:

$i = hour$ (0 h… 23 h)

$j = summer\ month$ (May… October)

$ENS_{ij} = average\ unitary\ energy\ savings\ during\ the\ hour\ i\ of\ a\ representative\ day$

$of\ the\ summer\ month\ j\ \left(\frac{Wh}{m^2}\right)$

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

$\Delta T = difference\ between\ outside\ and\ inside\ temperature\ in\ the\ building\ (K)$

$T_{summer\ setpoint} = set\ temperature\ in\ the\ HVAC\ System\ in\ summer (K)$

$T_{outdoors\,ij} = average\ temperature\ outside\ the\ buiding\ during\ the\ hour\ i\ of\ a\ represetative\ day$

$of\ the\ \ the\ summer\ month\ j\ (K)$

$\eta_{HVAC\,summer} =\ eficciency\ of\ the\ HVAC\ system\ \ in\ summer \approx \eta_{Heat\ Pump} =\ heat\ pump\ efficiency$

Average **energy savings** per m^2 of green roof during a representative **day** of a summer month can be calculated as follows:

$$ENS_j\left(\frac{Wh}{m^2 \cdot day}\right) = \sum ENS_{ij}\left(\frac{Wh}{m^2}\right)$$

Equation 6.14

Where:

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

$ENS_{ij}\ = average\ unitary\ energy\ savings\ during\ the\ hour\ i\ of\ a\ representative\ day$

$of\ the\ summer\ month\ j\ \left(\frac{Wh}{m^2}\right)$

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

$$ENS_{summer}\left(\frac{kWh}{m^2}\right) = \frac{\sum\left(ENS_j\left(\frac{Wh}{m^2 \cdot day}\right) \cdot N_{working\ days_j}(day)\right)}{1000} \qquad \textit{Equation 6.15}$$

Where:

$j = summer\ months$

$ENS_{summer} = average\ unitary\ energy\ savings\ during\ the\ summer\ \left(\frac{kWh}{m^2}\right)$

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

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

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

$$ES_{summer}\left(\frac{kg\ CO_2e}{m^2}\right) = ENS_{summer}\left(\frac{kWh}{m^2}\right) \cdot EF_{elec.count.}\left(\frac{kg\ CO_2e}{kWh}\right) \qquad \textit{Equation 6.16}$$

Where:

$ES_{summer}\left(\frac{kg\ CO_2e}{m^2}\right) = average\ unitary\ emissions\ savings\ during\ the\ summer\ \left(\frac{kg\ CO_2e}{m^2}\right)$

$ENS_{summer} = average\ unitary\ energy\ savings\ during\ the\ summer\ \left(\frac{kWh}{m^2}\right)$

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

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:

$$ENS_{GR+CV\ Vs.\ CV}\left(\frac{kWh}{m^2 \cdot year}\right) = ENS_{winter} + ENS_{summer} \qquad \textit{Equation 6.17}$$

Where:

$$ENS_{GR+CV\ Vs.\ CV} = annual\ average\ unitary\ energy\ savings\ by\ installing\ a\ greenroof\ over\ a\ conventional\ roof\ \left(\frac{kW}{m^2}\right)$$

$$ENS_{winter} = average\ unitary\ energy\ savings\ during\ the\ winter\ \left(\frac{kWh}{m^2}\right)$$

$$ENS_{summer} = average\ unitary\ energy\ savings\ during\ the\ summer\ \left(\frac{kWh}{m^2}\right)$$

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

$$ES_{GR+CV\ Vs.\ CV}\left(\frac{kg\ CO_2e}{m^2 \cdot year}\right) = ES_{winter} + ES_{summer} \qquad \textit{Equation 6.18}$$

Where:

$$ES_{GR+CV\ Vs.\ CV} = annual\ average\ unitary\ emissions\ savings\ by\ installing\ a\ greeenroof\ over\ a\ conventional\ roof\ \left(\frac{kg\ CO_2e}{m^2}\right)$$

$$ES_{winter} = average\ unitary\ emissions\ savings\ during\ the\ winter\ \left(\frac{kg\ CO_2e}{m^2}\right)$$

$$ES_{summer} = average\ unitary\ emissions\ savings\ during\ the\ summer\ \left(\frac{kg\ CO_2e}{m^2}\right)$$

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