1 SOLAR ENERGY

1.1 SOLAR COLLECTORS

Daily amount of thermal energy Q_T^{SC} produced by a solar collector plant can be estimated with the expression:

$$Q_T^{SC} = F_\Sigma^{SC} \cdot S_{tilted} \cdot \eta_{SC}, \tag{1.1}$$

where F_Σ^{SC} - total net surface of the solar field, m^2;

$$F_\Sigma^{SC} = F_{SC} \cdot n_{SC},$$

where F_{SC} - net surface of one solar collector, m^2; n_{SC} - number of solar collectors;

S_{tilted} - daily solar insolation on a tilted collector surface, kWh/m^2 per day;

η_{SC} - optical absorption coefficient, technical parameter of the collector installed.

Insolation on the tilted surface is calculated as [http://www.pveducation.org/pvcdrom]

$$S_{tilted} = \frac{S_{horizontal}\sin(\alpha + \beta)}{\sin\alpha} \tag{1.2}$$

where $S_{horizontal}$ - daily solar radiation on horizontal surface; data on the solar insolation are taken at https://power.larc.nasa.gov/data-access-viewer/;

α is the sun elevation angle;

β is the collector tilt angle measured from the horizontal, optimal tilt angle for solar collector being an angle equal to the latitude.

$$\alpha = 90 - \varphi + \delta, \tag{1.3}$$

where φ is the latitude;

δ is the declination angle calculated as:

$$\delta = 23{,}45 \cdot \sin\left(360 \cdot \frac{284 + d}{365}\right) \tag{1.4}$$

where d is the day of the year starting with January 1st (January 1st - 1, January 2nd – 2, etc).

The amount of water G_{HW} that can be heated by the installed solar collectors is found from the formula

$$Q_T^{SC} = G_{HW} \cdot c_W \cdot \Delta T, \tag{1.5}$$

where c_W – specific heat of water, $1.16 \cdot 10^{-3}$ kWh/(kg·°C);

ΔT - cold-to-hot water temperature difference, °C.

Consequently, daily amount of heated water, m^3:

$$G_{HW} = \frac{Q_T^{SC}}{c_W \cdot (T_{HW} - T_{CW})} \cdot 10^{-3} \qquad (1.6)$$

The annual quantity of the thermal energy produced by a solar collector plant, kWh_T:

$$Q_{T\_annual}^{SC} = \sum_{1}^{365} Q_{T\_i}^{SC} \qquad (1.7)$$

The quantity of saved fossil fuel, o.e., is assessed as

$$FF_{saved} = Q_{T\_annual}^{SC} \cdot b_T , \qquad (1.8)$$

where b_T – specific fossil fuel consumption for heat generation, kg/kWh (table 1.1).

Table 1.1 – Specific fuel consumption per kWh for different fuels

Fuel	*b*, kg/kWh
Natural gas	0,199
Fuel oil	0,284
Fuel oil	0,292
Fuel oil	0,274
Fuel oil	0,269
Hard coal	0,338
Lignite	0,364
Lignite briquettes	0,353
Coke	0,382

The quantity of saved green-house gases in CO2-eq is assessed as

$$Q_{CO2\text{-}eq} = e_{CO2} \cdot FF_{saved} \qquad (1.9)$$

where e_{CO2} is emission factor, kg-CO2/kg of fuel (table 1.2)

Table 1.2 - Green-house gas emission factor e_{CO2} of fossil fuels (Source: Recknagel 07/08, Annex)

Fossil fuel burnt in power plant	e_{CO2}, $kgCO_2/kWh$
Hard coal	0,350
Coke	0,420
Lignite	0,410
Lignite briquettes	0,380
Fuel Oil EL	0,312
Heavy fuel Oil	0,290
Natural Gas L	0,200
Natural Gas H	0,200
Town gas	0,200

1.2 Photovoltaic plant

Daily output of a photovoltaic module, $W_{\mathrm{E}}^{\mathrm{PhM}}$, Wh, is calculated with formula:

$$W_{\mathrm{E}}^{\mathrm{PVM}} = P_{\mathrm{PVM}} \cdot k_{\mathrm{cor}}^{\mathrm{PVM}} \cdot T_{\mathrm{SH}} \ , \qquad (1.10)$$

where P_{PhM} - rated capacity of the module, W;

$k_{\mathrm{cor}}^{\mathrm{PhM}}$ - correction factor allowing for module power loss due to effects of temperature increase and light intensity change, equal to 0.7.

T_{SH} - number of peak sun hours, taken identical to the average daily solar insolation, $T_{\mathrm{SH}} = S_{\mathrm{SI}}^{\mathrm{d}}$, as PV modules are rated at the input solar radiation of 1kW/m^2.

Consequently, daily amount of the electricity produced by a photovoltaic module, Wh:

$$W_{\mathrm{day}}^{\mathrm{PVM}} = P_{\mathrm{PVM}} \cdot S_{\mathrm{SI}}^{\mathrm{d}} \cdot k_{\mathrm{cor}}^{\mathrm{PVM}} \cdot . \qquad (1.11)$$

The annual amount of electric energy $W_{\mathrm{annual}}^{\mathrm{PhP}}$, kWh, produced by a photovoltaic plant, is calculated as:

$$W_{\mathrm{annual}}^{\mathrm{PVP}} = \sum_{i=1}^{365} (n_{\mathrm{PVM}} \cdot W_{\mathrm{day}i}^{\mathrm{PVM}}) \cdot 10^{-3} \qquad (1.12)$$

where n_{PVM} - number of PV modules in the plant.

The quantity of saved fossil fuel, , is assessed with (1.8)

$$FF_{saved}^{PVP} = W_{\mathrm{annual}}^{\mathrm{PVP}} \cdot b_{\mathrm{E}} \ ,$$

where b_{E} – specific fossil fuel consumption for electricity generation, kg/kWh (see table 1.1).

The quantity of saved green-house gases in CO_2-eq is assessed with (1.9)

$$Q_{\mathrm{CO2\text{-}eq}} = e_{\mathrm{CO2}} \cdot FF_{saved}^{PVP}$$

Useful internet sites:
[http://www.pveducation.org/pvcdrom, https://pasolar.ncat.org/lessons.php]

2. WIND POWER

The power of the moving air is the flow rate of kinetic energy of air mass m_{air} moving with speed V_{air}:

$$P = \frac{m_{air} \cdot V_{air}^2 \cdot}{2} \tag{2.1}$$

The mass flow rate of the air, kg/s, is

$$m_{air} = \rho \cdot A \cdot V ,$$

where ρ is air density, 1.221 kg/m^3 at the sea level at 1 atm and 18 C, for higher site elevation H_m it is calculated as $\rho = \rho_0 - (1.194 \times 10^{-4} H_m)$;

A –area swept by the rotor blades, m^2;

V – the air velocity, m/s.

Wind turbine rotor only extracts part of the power of the moving air and output power is determined as:

$$P_{WT} = \frac{\rho \cdot A \cdot V^3 \cdot}{2} \cdot C_p , \tag{2.2}$$

where C_p – rotor efficiency or power coefficient of the wind turbine rotor.

C_p shows fraction of the upstream wind power that is extracted by the rotor blades and fed to the generator. The theoretical maximum value of C_p is 0.59.

Consequently,

$$P_{WT} = \frac{\rho \cdot A \cdot V^3 \cdot}{2} \cdot 0.59 \tag{2.3}$$

In modern three-blade wind turbine designs, C_p ranges between 0.39 and 0.44.

For horizontal-axis wind turbines, the rotor-swept area is

$$A = \frac{\pi \cdot D_{rot}^2 \cdot}{4} , \tag{2.4}$$

where D_{rot} – the wind turbine rotor diameter, m^2.

Then the turbine output power in kW can be calculated as

$$P_{WT} = 4.81 \cdot 10^{-4} D_{rot}^2 \cdot V_h^3 \cdot C_p , \tag{2.5}$$

where V_h – the speed of wind at the height of the wind turbine rotor, m/s.

For the vertical-axis turbine, the swept area is

$$A = \frac{2}{3}(\text{max rotor width at the center})/(\text{the rotor height}) \tag{2.6}$$

The overall wind turbine efficiency C_p is a product of the turbine components efficiency:

$$C_p = \eta_{rot} \cdot \eta_{gear} \cdot \eta_{gen} , \tag{2.7}$$

and wind turbine output power is

$$P_{WT} = 4.81 \cdot 10^{-4} D_{rot}^2 \cdot V_h^3 \cdot \eta_{rot} \cdot \eta_{gear} \cdot \eta_{gen} \tag{2.8}$$

Specific rated capacity (SRC) of the wind turbine, kW/m2:

$$SRC = 0.615 \cdot 10^{-3} \cdot V_h^3 \cdot \eta_{rot} \cdot \eta_{gear} \cdot \eta_{gen} , \tag{2.9}$$

The wind speed increases with height in accordance with the formula:

$$\frac{V_h}{V_0} = \left(\frac{h}{h_0} \right)^{\alpha} \tag{2.10}$$

где V_h – wind speed estimated at height h (i.e. the tower height);

V_0 – wind speed measured at the reference height h_0; as a rule, h_0 = 10 m - the height of weather station)

α – ground surface friction coefficient.

The friction coefficient depends on the terrain type and is low for smooth terrains and high for rough terrains (table).

Table 2.1 – Friction coefficient α of various terrains

Terrain type	Friction coefficient a
Lake, ocean, smooth hard ground	0.10
Foot-high grass on level ground	0.15
Tall crops, hedges, shrubs	0.20
Wooded country with many trees	0.25
Small town with some trees and shrubs	0.30
City area with tall buildings	0.40

Consequently,

$$V_h = V_0 \cdot \left(\frac{h}{h_0} \right)^{\alpha} \tag{2.10}$$

The annual amount of electric energy W_{annual}^{WF}, kWh, produced by a wind farm, is calculated as:

$$W_{annual}^{WP} = \sum_{i=1}^{365} (24 \cdot n_{WT} \cdot W_{dayi}^{WP}) , \tag{2.11}$$

where 24 – number of hours per day;

n_{WT} - number of PV modules in the plant.

The quantities of saved fossil fuel and green-house emissions are calculated with (1.8) and (1.9), respectively.

Assignment

№	Wind turbines	Photovoltaics	Solar collectors	Location
1.	5 Enercon E82/2000 (*h*=100m)	12500 380W Solar modules	8 solar collectors 2.88м^2, $\angle$50°, S	
2.	12 Nordex N43-600	1168 365W Solar modules	20 solar collectors 2.1м^2, $\angle$30° SSW	
3.	9 MHI Vestas Offshore V112/3300 (100m, sea)	74600 225W Solar modules	12 solar collectors 2.65м^2, $\angle$30° SSE	
4.	14 Goldwind GW87/1500 (*h*=85m)	284 500W Solar modules	20 solar collectors 2.5м^2, $\angle$30° S	
5.	7 Siemens SWT-3.0-101 (*h*=95m, sea)	41612 370W Solar modules	10 solar collectors 3.15м^2, $\angle$30° S	
6.	11 Fuhrlaender WTU3.2/120	214400 215W Solar modules	24 solar collectors 2.46м^2, $\angle$30° SW	
7.	21 Nordex N43-600	128660 365W Solar modules	48 solar collectors 2.28м^2, $\angle$50° S	
8.	91 Goldwind GW140/3000 (*h*=100m)	1388 495W Solar modules	12 solar collectors 2.1м^2, $\angle$30° SSE	
9.	10 Nordex N90/2300 (*h*=90m)	424000 320W Solar modules	32 solar collectors 2.42м^2, $\angle$50° SSW	
10.	7 Enercon E126/3000 (*h*=95m)	424 485W Solar modules	18 solar collectors 3.81м^2, $\angle$50° S	

The data on the wind turbines are to be taken at internet site https://www.thewindpower.net/

The data on the PV modules are to be taken at internet site

1 - https://mpsolar2018.en.made-in-china.com/product/vKRnrPdyggYm/China-300W-High-Quality-Poly-PV-Solar-Module-for-Solar-Power-System.html

2 - http://shop.solardirect.com/product_info.php?cPath=23_161_165_194_623&products_id=2079

3 - http://shop.solardirect.com/product_info.php?cPath=23_161_165_194_561&products_id=2095

4 - http://www.viasolis.eu/page/glass-glass-modules.109/

The data on the solar collectors are to be taken at internet site https://www.vaillant.info/customers/products/solar-thermal-collector-aurotherm-exclusive-vtk-640.html