Wood to electricity, direct and indirect (via methane as secondary fuel), and comparison to photovoltaic production

a)
Using photosynthesis efficiency of 0.06% from a yearly mean irradation of 140 W/m^2 (Switzerland), how much dry wood (15% humidity) is grown every year renewably in all Swiss forest (11'000 km^2, 26% of total area) ?
Exploiting this wood via combustion and steam cycles into electricity with a conversion of 20% (10 MWth plants), how much electricity can this generate annually?

140 W/m^2 * 0.06% = 0.084 W/m^2
0.084 W/m^2 * 11. 10^9 m^2 = 924 MW
924 MW * (3600*24*365.25) = 29.16 PJ
LHV of 15% humidity wood = 20 * (1 – 1.14*0.15) = 20 * 0.83 = 16.6 MJ/kg
Hence 29.16 PJ / 16.6 MJ/kg → 1.76 10^9 kg = 3.1 mio m^3 (density 0.56 kg/m^3)
29.16 PJ * 20% electrical efficiency = 5.83 PJ = 1.62 TWh
This is just 2.5% of Swiss electrical generation (65 TWh).

b)
Converting instead this wood via gasification into methane (wood-to-methane 71%) and then this methane into electricity with fuel cells (60%), how much electricity can be produced annually?

29.16 PJ wood * 71% = 20.7 PJ methane
20.7 * 60% electrical efficiency = 12.42 PJ = 3.45 TWh, more than double that of wood combustion + a Rankine cycle.
(This even neglects potential further gains in efficiency through thermal integration.)

c)
Using the solar irradiation in photovoltaic panels (20% efficient) installed on all ca. 138 km^2 well oriented roof surface (Switzerland), how much solar electricity can this generate ?

140 W/m^2 * 138.10^6 m^2 * 20% efficiency = 3.864 GW
3.864 GW * (24*365.25) = 33.9 TWh
This is over half of Swiss electrical generation (65 TWh).

d)
Compare and comment the three routes a to c.
The (real) forest area is 80 times larger than the (theoretical) PV panel area for the whole country. However, capture efficiency of solar irradiation is (20%/0.06%)=333 times more efficient with direct PV than for biomass growth, and biomass to electrical conversion loses another factor of 5 (20%). In the end, PV-electricity is then (1666 efficiency advantage to 80 area disadvantage) 20 times larger than wood-electricity. The secondary fuel route from wood gasification + electrochemical conversion is more efficient than direct combustion, for electricity generation.

Compute the yearly tonnes of biomasses needed to feed the following plant:

Electrical power: 5 MWe

Load factor: 80%

Electrical efficiency: 25%

HHV on dry and ash-free basis for all biomasses: 20 MJ/kg (50% C, 44% O, 6% H – all weight%)

The use of HHV means that the burning process will be followed by a condensation process to retrieve any heat going into evaporating the water through combustion. Therefore, humidity, in the case of HHV, only affects the amount by mass of 'fuel' to be burnt inside the total mass. As of the ash, the effect of ash combustion is negligible resulting only in, again, a 'dilution' in the mass of 'fuel' to be burnt. Taking these points in consideration, the following equation will estimate the HHV of humid biomass with a percentage of ash:

$$HHV_{humid+ash} = HHV_{dry} \times (1 - W_{water} - W_{ash})$$

Bagasse: 50% humidity, 4% ash => 20 MJ/kg * 46% = 9.2 MJ/kg

Rice residue: 12% humidity, 16% ash => 20 MJ/kg * 72% = 14.4 MJ/kg

Wood: 25% humidity, 1% ash => 20 MJ/kg * 74% = 14.8 MJ/kg

Nut shells: 7.5% humidity, 0.5% ash => 20 MJ/kg * 92% = 18.4 MJ/kg

Underlying assumption: boiler efficiency is the same, independent of the biomass (which is not quite true because wet or high-ash biomass will lower the boiler thermal efficiency).

So the input energy is 9.2 to 18.4 MJ/kg (simple to double).
For 5 MWe and 25% electrical efficiency, thermal input is 20 MW_{th}. For a load factor of 80%, operation time is 8760h * 80% = 7000h.
Hence energy input must be 20 MW * 7000h = 140 GWh_{th} = 504 TJ/yr.
The annual biomass feed is then:
504 TJ/yr / 18.4 MJ/kg = 27.4 ktonne for nuts
504 TJ/yr / 14.8 MJ/kg = 35 ktonne for rice residues
504 TJ/yr / 14.8 MJ/kg = 34 ktonne for wood or rice residues
504 TJ/yr / 9.2 MJ/kg = 54.8 ktonne for bagasse

Another way of representing this is 140 GWh_{th} / 54.8 ktonne = 2.55 kWh_{th} per kg of bagasse, to 5.1 kWh_{th} per kg of nuts, for an electricity generation (25%) of 0.64 kWh_{el} to 1.28 kWh_{el} per kg of biomass.