What are the renewable alternatives to fossil fuels?

Below is given the energy use in EJ (exajoules, 10^{18} J) in 2023 by fuel source : (https://www.energyinst.org/statistical-review/resources-and-data-downloads)

Oil	Natural Gas	Coal	Nuclear energy	Hydro electric	Renew-ables	Total
196,43	144,37	164,03	24,57	39,651	50,58	619,63

We want to try and estimate by order-of-magnitude what is needed to replace fossil fuels by renewables, using some very crude assumptions :
Oil is used for mobility
Gas is used for heating
Coal is used for electricity
Hydro and nuclear will remain constant

Approach :

1. Apply meaningful conversion efficiencies for each of the 3 fossil resources + uses
2. Choose which of the 3 fossil resources you'll replace by which renewable resource among the following :
   - Solar PV
   - Wind
   - Wood
   - Biowastes for biogas
   - Biocrops for liquid biofuels
3. Find the conversion efficiencies, load factors and m^2 requirements of the renewable technologies to propose estimates
4. Discuss the findings

Solution :

1. Assumed efficiencies :

Oil for mobility : 25% => 196,43 EJ become ~50 EJ mobility final use (≈14000 TWh)
Gas for heating : 90% => 144,37 EJ become ~130 EJ heat final use
Coal for electricity : 40% => 164,03 EJ become ~66 EJ (=18'000 TWhe) electricity use

(Remark: actual electricity production from coal is ~10'000 TWhe, so obviously coal is also used for other purposes, and average efficiency in power plants may be lower, and the load factor <100%, but the order of magnitude fits.)

2. Choices for replacement:

Solar PV and wind => electricity
Wood => heating
Biogas => heating (alternatively for mobility)
Biocrops => liquids => mobility

3. Conversion efficiencies and land use:

Solar:
20% efficiency from 1 kW input, annual load factor 15%
=> 200 W/m^2 x 15% of 8760 h (1314 h) ≈ 250 kWh / m^2
To generate 18'000 TWhe/yr, 18.10^{15} / 250.10^3 = 72.10^9 m^2 solar PV panels are needed = 72'000 km^2, roughly the combined size of Switzerland + Belgium.

Emerged land of the continents = 44.6 Mkm^2 (Asia) + 30 Mkm^2 (Africa) + 24.5 Mkm^2 (N-Am) + 17.8 Mkm^2 (S-Am) + 10 Mkm^2 (Europe) + 7.7 Mkm^2 (Australia) = 134.6 Mkm2
In other words, 72.10^3 / $134.6.10^6$ = 0.0535% of emerged land would be occupied by PV panels, or 1 m^2 of every ~2000 m^2. It might seem doable, but it does seem a lot.

Wind:
1 MWe per average turbine, annual load factor 25% (2190 h/yr)
=> 2190 MWhe/yr per turbine. This would be a ~75 m turbine and we assume turbines to be spaced at least 10 diameters apart to be undisturbed, hence at least 750 m apart. To simplify, assume then that we can put 1 such turbine every km^2.
To generate 18000 TWhe/yr, 18.10^{15} / 2.19 10^9 = 8.2 million such wind turbines are needed, spread over 8.2 Mkm^2. With 134.6 Mkm^2 available land, there would be 1 turbine roughly every 15 km or so, all over the continents. In practice, they would be concentrated in wind farms, and they can be put off-shore in seas too, and they become bigger (up to 10 MWe per turbine !), which would greatly reduce the land impact.

Wood:
There is about 32 Gtoe (=1344 EJ) of solar energy stored in Earth's forests every year, occupying around 56 Mkm^2 of land (11% of emerged land). Wood energy use was about 22 EJ (2 billion m^3) in 2023, hence <2% of the wood yearly grown. Pushing wood use to 144 EJ/yr to replace natural gas consumption would then represent a 7-fold increase in wood energy use, not impossible from a sustainability point of view, but likely challenging in terms of logistics.

Biogas:
There is about 4 Gtoe (=17 EJ) of energy grown in agriculture per year, mainly to feed humans and animals. Only a fraction of this can be recovered as biogas energy, which can be complemented with biogas from manure, as roughly 50-50%. Order-of-magnitude biogas production could then be ~10 EJ/year, far from negligible but far from replacing all of natural gas use. This is essentially because it is a 'waste stream'.

Bioliquids:
Global liquid biofuel production now is ~200 billion L/yr (60% bioethanol (26 MJ/l), 40% biodiesel (35 MJ/L)), equivalent to ~3 EJ ethanol + ~3 EJ biodiesel, or 6 EJ together. This requires enormous surfaces. Taking rough figures of 5000 L ethanol/hectare/yr and 1000 L biodiesel/hectare/yr (1 hectare = 10'000 m^2), one finds areas of
120 billion L ethanol/5000 L/ha = 24 Mha = 0.24 Mkm^2 = 6 times Switzerland
80 billion L biodiesel/1000 L/ha = 80 Mha = 0.8 Mkm2 = 20 times Switzerland
for just 6 EJ/yr of bioliquid fuel, whereas oil consumption is 196 EJ/yr.

4. Discussion:

Clearly renewable mobility fuel is massively limited, going the traditional way. Alternatives are needed, either through mobility electrification, or using hybrid drives or H_2, or through other ways of making liquid fuels, e.g. from wood or via electrolysis and chemical synthesis. One also notices that 10 EJ/yr of biogas would not be silly to use as alternive transport fuel, in particular for heavy vehicles.

Heating need from natural gas seems possible to be replaced by renewable sources, considering not only wood, but also from (solid) wastes (incineration), and partly lower temperature sources where possible (heat pumps, solar thermal, district heat,...).

Electricity from coal seems also possible to be replaced by renewable electricity sources when using a combination from PV, wind, more hydro, some geothermal electricity (marginal), tidal & wave electricity (marginal) etc. Nonetheless huge quantities of PV panels and wind turbines would be needed. Specifically, an intermediate storage is needed, which reduces efficiencies and will further increase the amount of total installed power. Adding to this a shift to electrical mobility and to electrical heating (heat pumps), the requirements become massive.