

Energy Economics, Winter Semester 2024-5

Lecture 2: Energy Balances

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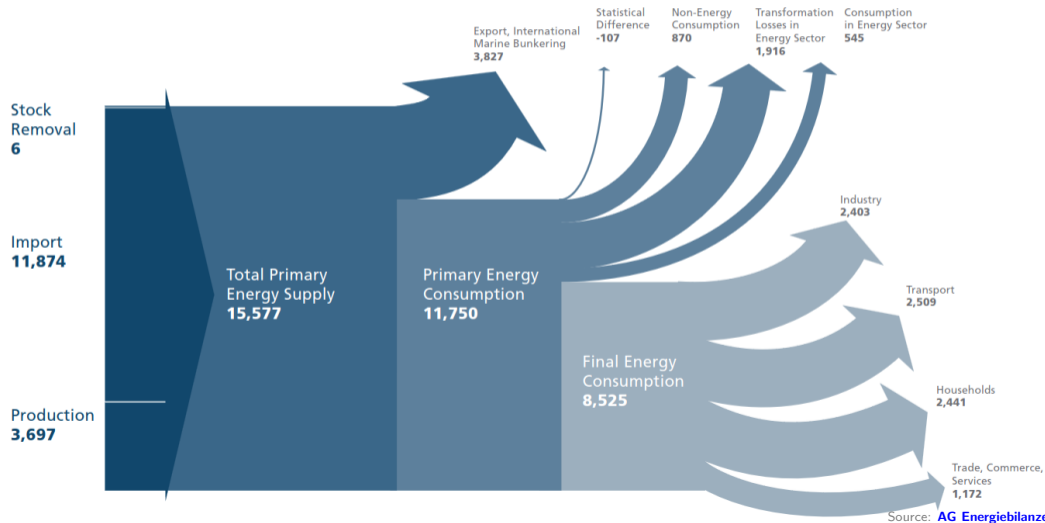
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1. Measuring Energy
2. Energy Balances

Measuring Energy

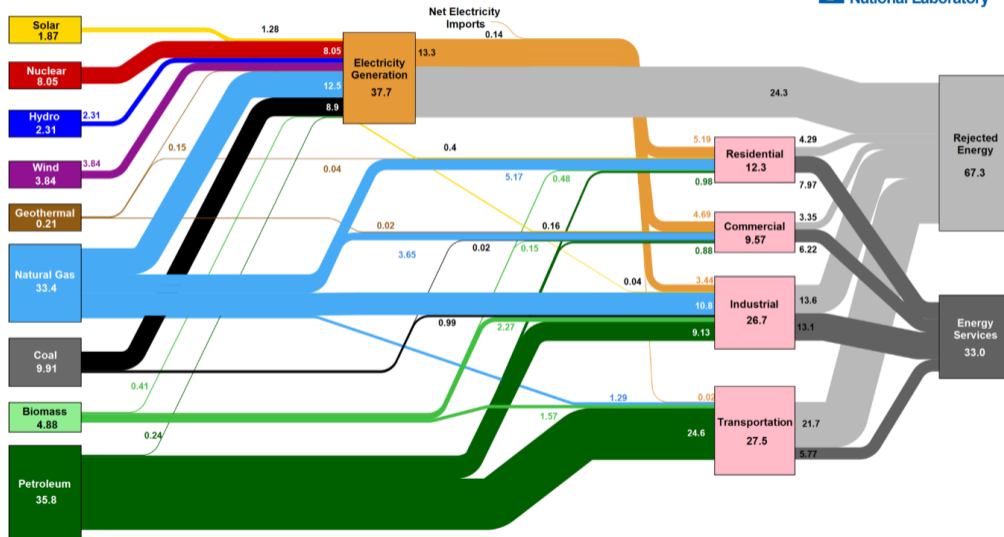
Goal: Understand Energy Flow Through the Economy

Example: **energy balance** for Germany in 2022 in Petajoule (PJ)



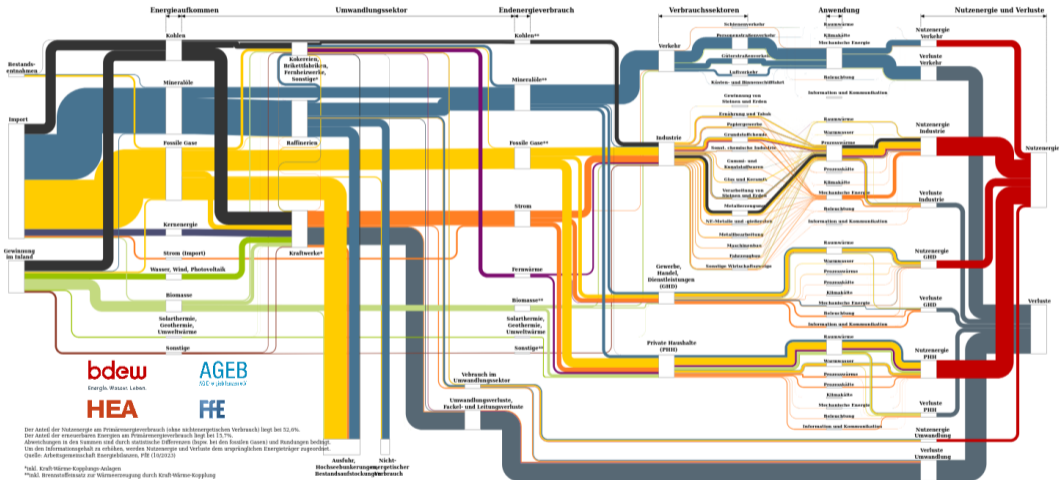
Example: Sankey diagram for US in 2022

Estimated U.S. Energy Consumption in 2022: 100.3 Quads



Example: Useful energy (Nutzenergie) for Germany 2021

Energieflussbild der Bundesrepublik Deutschland 2021 in PJ



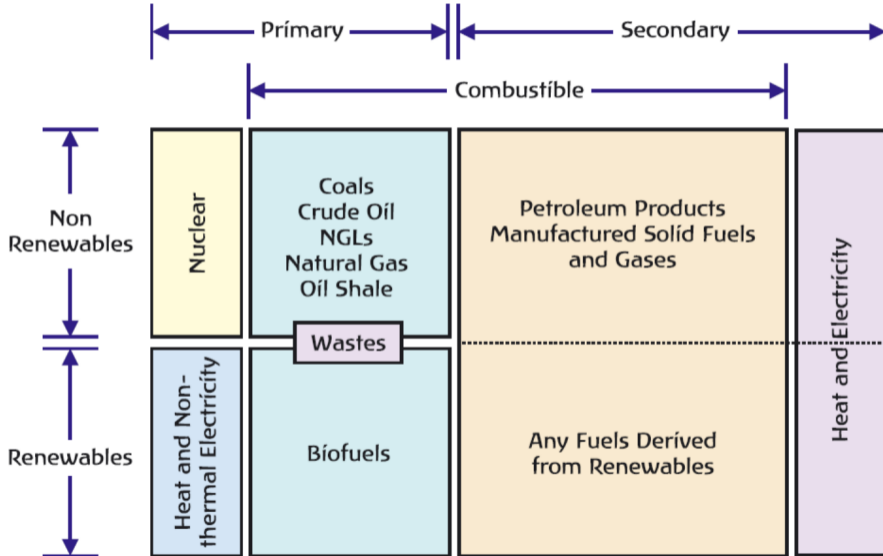
Output Input	Mechanical energy	Thermal energy	Chemical energy	Electricity	Radiation
Mechanical energy	–	Frictional heat	–	Hydropower turbine	–
Thermal energy	Heat engine	–	Thermo- chemistry	Electrical generator	–
Chemical energy	Combustion engine	Boiler	–	Fuel cell	Gas lamp
Electricity	Electric engine	Induction heater	Electrolysis	–	Electric bulb
Radiation	Laser	Microwave oven	Solar chemistry	Photovoltaic	–
Nuclear energy	–	Nuclear reactor	–	–	Radioactivity

Definitions of energy are oriented towards conventional energy sources like coal, oil and gas.

- **Primary energy** is energy as found in nature before it undergoes any transformation (crude oil, coal, gas, biomass, nuclear, wind, solar).
- **Secondary energy** is energy after conversion processes, either chemical or physical (refined fuels like gasoline, electricity from a coal power plant).
- **Final energy** is the energy as it is sold to end users (electricity, refined fuels like gasoline, gas for building heating).
- **Useful energy** is the energy after conversion by the consumer, available to be used (heat in a home, light, mechanical work).
- **Energy services** is what the consumer actually wants: a warm home, transportation from A to B, manufactured goods, etc.

The two most commonly used definitions are **primary** and **final** energy, since they are **easier to measure** in a fossil-fuelled world. With more focus on renewables and electrification, this **may change!**

Classification of Energy Sources



Joule (J) is the SI unit of energy.

Conventional primary energy sources are often measured in units corresponding to their natural form: volume, mass etc.

We can convert from measurements of mass [kg] and volume [m³] to energy units using the **calorific value** [J/kg, J/m³], which measures the heat from combustion.

Example: the unit **tonne of oil equivalent** (toe) is the energy generated by burning one metric ton of oil. Since the calorific value of oil is 41.88 MJ/kg, we have

$$1 \text{ toe} = 41.88 \text{ GJ}$$

[Reminder: k = kilo = 1e3, M = Mega = 1e6, G = Giga = 1e9, T = Tera = 1e12, P = Peta = 1e15, E = Exa = 1e18.]

Lower Heating Values of Energy Fuels

	Density	Energy [10^9 J]	Remarks
1 t Crude oil	0.86 g/cm ³	39–43	Mean: $41.9 \cdot 10^9$ J
1 Barrel (bbl) crude oil		5.7	=159 l (ca. 50/365 t.o.e.)
1 t Heating oil el.	0.84 g/cm ³	42.5	at 15–20 °C
1 t Gasoline	0.75 g/cm ³	43.1	at 15–20 °C
1 t Methanol (CH ₃ OH)	0.80 g/cm ³	19.7	
1 t Ethanol (C ₂ H ₅ OH)	0.80 g/cm ³	26.9	
1 t Liquefied Petroleum Gas LPG	0.53 g/cm ³	45.9	at 2–18 bar
1 t Liquefied Natural Gas LNG	0.47 g/cm ³	47.2	at –164 °C
1 t Hydrogen (LH ₂)	0.071 g/cm ³	120.4	at –252 °C
1000 m ³ Natural gas L	0.82 kg/m ³	33.4	Mean: $35.6 \cdot 10^9$ J
1000 m ³ Natural gas H	0.79 kg/m ³	36.6	
1000 m ³ Compressed gas CNG	156 kg/m ³	7000	at 200 bar
1000 m ³ Petroleum gas		40.7	
1000 m ³ Methane (CH ₄)	0.65 kg/m ³	35.8	
1000 m ³ Propane (C ₃ H ₈)	1.87 kg/m ³	86.7	
1000 m ³ hydrogen (H ₂)	0.09 kg/m ³	10.8	
1000 m ³ Liquefied hydrogen (H ₂)	15.6 kg/m ³	1950	at 200 bar
1 t Hard coal		29–35	Mean $29.3 \cdot 10^9$ J
1 t Lignite		7.5–13	
1 t Wood	0.6 g/cm ³	14.6	$3.5 \cdot 10^6$ kcal
1 t Uranium oxide (U ₃ O ₈)		414'000	Light Water Reactor LWR

- **Lower Heating Value (LHV)** is the maximum amount of usable heat from combustion without counting the condensation enthalpy of water vapor contained in the exhaust gas.
- **Higher Heating Value (HHV)** includes the condensation enthalpy of water vapor contained in the exhaust gas. It is always higher than the LHV (e.g. 11% higher for methane).

Fuel	State at ambient temperature and pressure	HHV (MJ/kg)	LHV (MJ/kg)
Hydrogen	Gas	141.9	119.9
Methane	Gas	55.5	50
Ethane	Gas	51.9	47.8
Gasoline	Liquid	47.5	44.5
Diesel	Liquid	44.8	42.5
Methanol	Liquid	20	18.1

LHV is most commonly used in European statistics. HHV becomes relevant in e.g. condensing combined heat and power plants (CHP) where vapor is condensed.

Power is the rate of consumption of energy.

It is measured in **Watts**:

$$1 \text{ Watt} = 1 \text{ Joule per second}$$

The symbol for Watt is W, $1 \text{ W} = 1 \text{ J/s}$.

$$1 \text{ kilo-Watt} = 1 \text{ kW} = 1,000 \text{ W}$$

$$1 \text{ mega-Watt} = 1 \text{ MW} = 1,000,000 \text{ W}$$

$$1 \text{ giga-Watt} = 1 \text{ GW} = 1,000,000,000 \text{ W}$$

$$1 \text{ tera-Watt} = 1 \text{ TW} = 1,000,000,000,000 \text{ W}$$

At full power, the following items consume:

Item	Power
New efficient lightbulb	10 W
Old-fashioned lightbulb	70 W
Single room air-conditioning	1.5 kW
Kettle	2 kW
Factory	~1-500 MW
CERN	200 MW
Germany total demand	35-80 GW

If all energy is electrified in 2050 and energy consumption equalises between nations, the average electricity consumption of the world would be around 12 TW.

Suppose half is met with wind (capacity factor 33.3%) and half is met with solar PV (capacity factor 16.6%). [Capacity factor = average generation / capacity.] How much wind and solar capacity does the world need (assuming perfect lossless storage)?

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Suppose half is met with wind (capacity factor 33.3%) and half is met with solar PV (capacity factor 16.6%). [Capacity factor = average generation / capacity.] How much wind and solar capacity does the world need (assuming perfect lossless storage)?

Wind: $6 \text{ TW} / 0.333 = 18 \text{ TW}$ (around 900 GW was installed by 2022)

Solar: $6 \text{ TW} / 0.166 = 36 \text{ TW}$ (around 1050 GW was installed by 2022)

If installed wind density on average is 10 MW/km^2 and solar is 72 MW/km^2 , what percentage of world land (149 million km^2) is taken with each?

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Wind: $18 \text{ TW}/(10 \text{ MW/km}^2) = 1.8 \text{ million km}^2$ (around 1.2% of total land = area of Indonesia)

Solar: $36 \text{ TW}/(72 \text{ MW/km}^2) = 0.5 \text{ million km}^2$ (around 0.3% of total land = area of Spain)

Nota Bene:

- Wind doesn't interfere with other land uses like agriculture; can also be built offshore
- 10 MW/km^2 is a **local** maximum installation density for wind, but to allow wind replenishment over large areas 2 MW/km^2 is suitable as a **wide-area** limit
- Solar can be rooftop or combined with agriculture = agrivoltaics

In the electricity sector, energy is usually measured in 'Watt-hours', Wh.

1 kWh = power consumption of 1 kW for one hour

E.g. a 10 W lightbulb left on for two hours will consume

$$10 \text{ W} * 2 \text{ h} = 20 \text{ Wh}$$

It is easy to convert this back to the SI unit for energy, Joules:

$$1 \text{ kWh} = (1000 \text{ W}) * (1 \text{ h}) = (1000 \text{ J/s}) * (3600 \text{ s}) = 3.6 \text{ MJ}$$

Germany consumes around 600 TWh per year, written 600 TWh/a.

What is the *average* power consumption in GW?

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What is the *average* power consumption in GW?

$$\begin{aligned}600 \text{ TWh/a} &= \frac{(600 \text{ TW}) * (1 \text{ h})}{(365 * 24 \text{ h})} \\ &= \frac{600}{8760} \text{ TW} \\ &= 68.5 \text{ GW}\end{aligned}$$

multiply by:	GJ	Toe	MBtu	MWh
GJ	1	0.024	0.948	0.278
Toe	41.868	1	39.683	11.630
MBtu	1.055	0.025	1	0.293
MWh	3.600	0.086	3.412	1

Units used in the United States:

- British thermal unit (Btu), 1 million Btu = MBtu (often written MMBtu) = 0.293 MWh
- Quad = $1e15$ Btu = 293 TWh

Efficiency of an energy conversion device (e.g. power plant, vehicle engine):

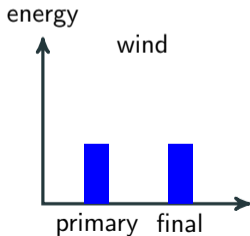
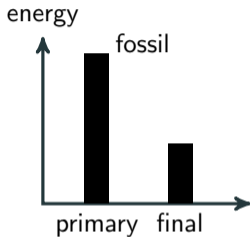
$$\text{Efficiency, } \eta = \frac{\text{Useful energy output}}{\text{Energy input}}$$

Example: How much natural gas is required for generating 100 MWh of electricity in a gas power plant with an efficiency of 50%?

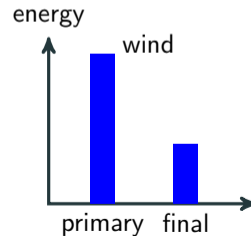
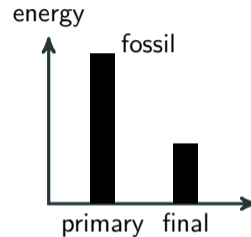
How to value primary energy of carriers which do not have a calorific value, e.g. wind, solar PV, hydroelectricity?

- **Fictive Efficiency Principle:** (also known as 'Physical Energy Accounting Method' or 'Direct Equivalent Method') (most common: used by IEA, OECD, Eurostat, IPCC) assume there is a 1-to-1 correspondence between primary energy and electricity for wind, solar, hydro (i.e. 100% conversion efficiency)
- **Substitution Principle:** (also know as the 'Input-Equivalent Method') (used by BP) assume the conversion efficiency from primary energy to electricity is the same as in a thermal (fossil or nuclear) powerplant (e.g. 35-45%)
- **Efficiency Principle:** actual efficiency of respective technology (hydro 80-90% gravitational potential energy of water to electricity, wind 30-55% kinetic energy of air to electricity, solar 10-25% radiation to electricity)

Fictive Efficiency Principle



Substitution Principle



Suppose 50% of electricity is provided by wind and solar, the rest by fossil plants with 33% efficiency.

What is the fraction of renewables in primary energy for electricity:

1. Using the Fictive Efficiency Principle
2. Using the Substitution Principle

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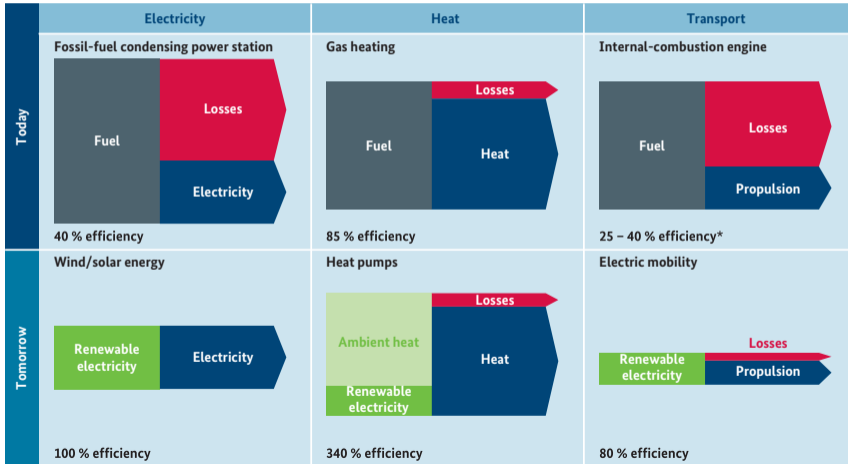
1. $\frac{50}{50+50/0.33} \% = \frac{50}{50+150} \% = 25\%$

2. 50% (since we assume renewables need as much primary energy for each unit of electricity as a thermal plant)

Bad faith actors will often present renewable shares in terms of primary energy to make it look small.

Primary and final energy change with electrification

Primary energy in grey and green; useful energy in blue. NB: Also in **industry**, electrification of process heat can be more efficient since the heat can be focused better than e.g. burning gas.



* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

Switching from thermal power plants to wind, solar and hydro leads to an **automatic decline in primary energy** using the Fictive Efficiency Principle, since thermal losses are no longer counted.

With electrification and efficiency, **final energy also declines** (compare gasoline required for a car versus electricity need; similarly natural gas for boiler versus electricity for a heat pump).

Both primary and final energy would decline! Primary by $\sim 50\%$, final by $\sim 33\%$.

Expect roughly a **doubling electricity demand** (assuming widespread electrification of end demands, indirect electrification with H₂ and efficiency measures).

Electricity would become the dominant final energy, primary energy becomes less relevant.

Most important metrics become: fraction of electricity from non-emitting sources; efficiency of electricity meeting energy services.

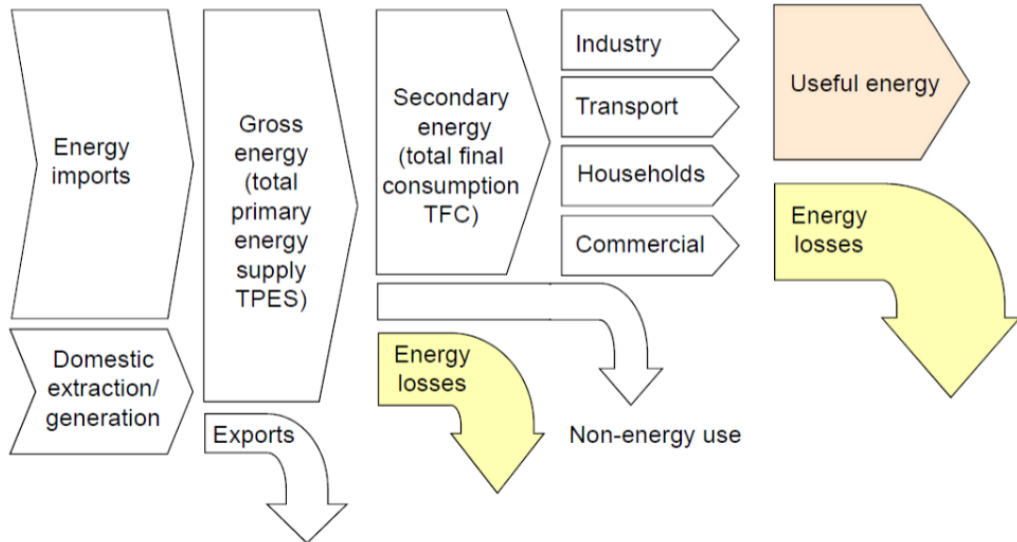
Energy Balances

Energy is always **conserved** as it flows through the energy system.

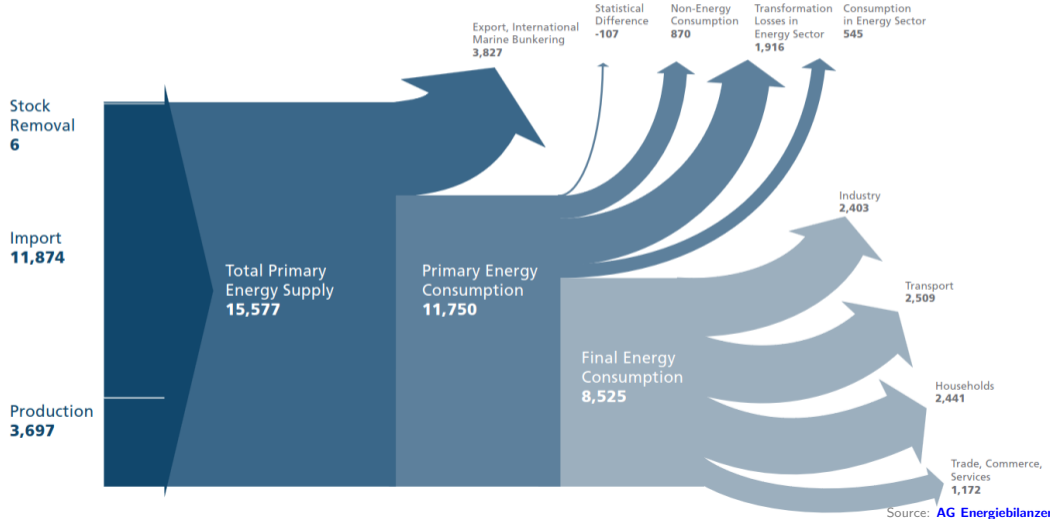
Energy balances tabulate this energy conservation at each step of conversion from primary energy supply to primary energy consumption to final energy to energy services for consumers.

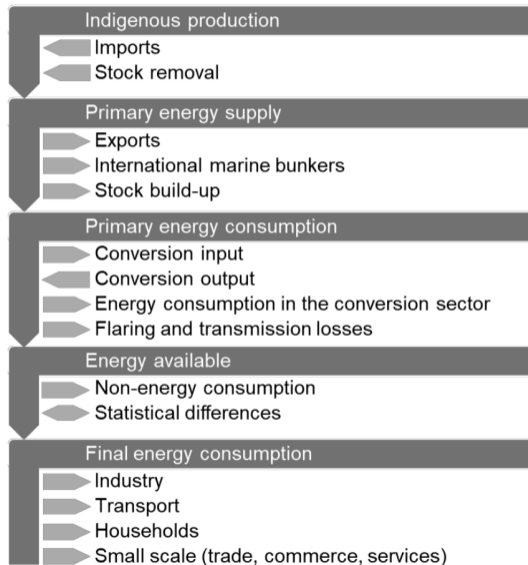
At each interface, inputs and outputs **balance**.





Example: **energy balance** for Germany in 2022 in Petajoule (PJ)





Simplified Energy Balance for EU28 in 2016

ktoe	EU28	2016	Total all products	Solid fuels	Oil (total)	Gas	Total Renewables	Wastes (non ren.)	Nuclear heat	Derived heat	Electricity
+	Primary production	R_100100	755,389	131,850	74,354	107,238	210,708	14,537	216,703		
+	Primary production receipt	R_100110	9,397		9,397						
+	From other sources (Recovered products)	R_100200	4,522	404	3,818	300					
+	Recycled products	R_100310	1,044		1,044						
+	Imports	R_100390	1,483,219	134,902	941,564	357,102	16,395	385		6	32,865
+	Stock changes	R_100400	21,263	11,807	3,423	5,944	89	0			
-	Exports	R_100500	579,508	38,239	411,746	87,613	10,574	29		5	31,301
-	Bunkers	R_100800	44,152		44,151	1					
-	Direct use	R_100912	10,559		10,559						
	Gross inland consumption	R_100900	1,640,615	240,724	567,142	382,969	216,618	14,893	216,703	1	1,564
	Transformation input	R_101000	1,294,958	224,492	654,689	125,132	61,875	11,027	216,703	768	272
+	Conventional Thermal Power Stations	R_101101	358,478	165,433	12,820	114,576	54,977	9,905		768	
+	Nuclear Power Stations	R_101102	216,703						216,703		
+	Coke-ovens	R_101104	36,597	36,215	355	27					
+	Blast-furnaces	R_101106	12,918	12,918							
+	Gas works	R_101107	695	674		21					
+	Refineries	R_101108	640,308		640,308						
+	District heating plants	R_101109	21,015	3,544	963	8,654	6,459	1,122			272
+	Patent fuel plants	R_101110	219	142	77						
+	BKB / PB Plants	R_101111	4,385	4,385							
+	Coal Liquefaction Plants	R_101112	901	901							
+	For Blended Natural Gas	R_101113	391		162		230				
+	Charcoal production plants (transformation)	R_101114	209				209				
+	Gas-to-Liquids (GTL) Plants (transformation)	R_101115									
+	Non-specified Transformation Input	R_101119	2,138	279	4	1,855					
	Transformation output	R_101200	963,032	31,378	640,125	20,223	62			59,192	212,054
+	Conventional Thermal Power Stations	R_101201	181,172							41,319	139,854
+	Nuclear power stations	R_101202	72,303							103	72,200
+	Coke-ovens	R_101204	34,193	27,365		6,828					
+	Blast-furnaces	R_101206	12,918			12,918					
+	Gas works	R_101207	477			477					
+	Refineries	R_101208	640,125		640,125						
+	Patent Fuel Plants	R_101210	173	173							
+	BKB / PB Plants	R_101211	3,840	3,840							
+	Charcoal production plants	R_101214	62					62			
+	District Heating Plants	R_101219	17,770							17,770	
	Exchanges and transfers, returns	R_101299	2,969		2,969		-65,240				65,240
	Consumption of the energy branch	R_101300	80,128	636	33,402	19,028	654	87		4,913	21,408
	Distribution losses	R_101400	26,372	35	53	3,093	24			5,554	17,612
	Available for Final Consumption	R_101500	1,205,158	46,938	522,093	255,939	88,886	3,780		47,957	239,565
	Final non-energy consumption	R_101600	97,773	1,763	82,480	13,530					
	Final energy consumption	R_101700	1,107,818	45,338	437,131	245,284	88,949	3,780		47,932	239,405
+	Industry	R_101800	276,823	33,774	27,513	86,242	22,542	3,524		16,112	87,115
+	Transport	R_101900	367,272	12	344,648	3,284	13,840				5,488
+	Other Sectors	R_102000	463,723	11,552	64,969	155,758	52,567	256		31,820	146,801
+	Services	R_102005	150,043	923	15,668	46,281	4,889	255		9,274	72,754
+	Residential	R_102010	284,832	9,507	33,139	105,175	45,369			22,148	69,494
+	Agriculture / Forestry	R_102030	24,079	1,082	12,992	3,426	2,132	1		252	4,194
+	Fishing	R_102050	1,426		1,236	2	46				142

- Gross inland consumption = Primary energy consumption = Production + Imports + Stock changes - Exports - Bunkers
- Bunkers is e.g. marine fuel stored at ports
- Around 330 Mtoe lost in transformation
- Final consumption = Final non-energy + Final energy consumption

- What is the average electrical efficiency of conventional power stations in the EU?
- What is the average electrical efficiency of nuclear power stations in the EU?
- What fraction of industry/transport/residential final energy consumption is electricity?
- What is non-energy consumption?

Includes more granular estimates of useful energy, efficiency, CO₂ emissions, breakdown e.g. industry by process.

From Joint Research Centre (JRC) of the European Commission.

<https://data.jrc.ec.europa.eu/dataset/jrc-10110-10001>

“The ‘Integrated Database of the European Energy Sector’ (JRC-IDEES) is a one-stop data-box that incorporates in a single database all information necessary for a deep understanding of the dynamics of the European energy system, so as to better analyse the past and to create a robust basis for future policy assessments. JRC-IDEES offers a consistent set of disaggregated energy-economy-environment data, compliant with the EUROSTAT energy balances, as well as widely acknowledged data on existing technologies. It provides a plausible decomposition of energy consumption, allocating it to specific processes and end-uses.”

JRC IDEES: Residential energy appliances

EU28 - Residential / specific electric uses	2010	2011	2012	2013	2014	2015
Final energy consumption (ktoe)	39,989.2	39,993.1	39,731.9	39,096.5	38,404.6	37,433.3
White appliances	15,205.1	15,357.2	15,569.5	15,703.9	15,963.3	16,147.7
Refrigerators and freezers	8,168.9	8,233.9	8,318.9	8,346.1	8,493.3	8,591.8
Washing machine	3,042.6	3,059.4	3,091.5	3,101.5	3,125.0	3,146.0
Clothes dryer	2,173.8	2,210.6	2,257.8	2,309.7	2,351.5	2,386.8
Dishwasher	1,819.7	1,853.4	1,901.4	1,946.6	1,993.6	2,023.2
Brown appliances	13,675.5	14,040.8	14,315.5	14,447.2	14,438.4	14,282.0
TV and multimedia	10,960.1	11,240.8	11,423.7	11,489.8	11,451.5	11,304.6
ICT equipment	2,715.5	2,800.0	2,891.8	2,957.4	2,986.9	2,977.3
Lighting and other electricity uses	11,108.5	10,595.0	9,846.8	8,945.3	8,002.9	7,003.6
Lighting	7,303.9	6,706.6	5,874.6	4,909.8	3,908.0	2,871.8
Other appliances (vacuum cleaners, irons etc.)	3,804.6	3,888.5	3,972.2	4,035.5	4,094.9	4,131.8
Total MW installed (in average operating mode)	1,793,429.5	1,803,111.1	1,808,318.2	1,798,855.9	1,785,602.2	1,760,140.1
White appliances	198,249.6	201,660.3	204,205.7	205,003.0	206,377.1	206,322.5
Refrigerators and freezers	10,843.3	10,929.5	11,042.4	11,078.6	11,273.9	11,404.6
Washing machine	46,970.9	46,636.3	46,501.5	46,097.7	46,013.4	45,439.7
Clothes dryer	103,001.4	106,198.2	108,150.6	108,822.7	109,478.3	109,645.3
Dishwasher	37,434.0	37,896.3	38,511.3	39,004.0	39,611.6	39,832.9
Brown appliances	113,857.3	116,148.5	118,037.1	118,656.8	118,007.3	116,001.5
TV and multimedia	71,905.5	73,160.4	73,861.1	73,760.4	72,967.2	71,455.6
ICT equipment	41,951.7	42,988.1	44,176.0	44,896.4	45,040.0	44,546.0
Lighting and other electricity uses	1,481,322.7	1,485,302.2	1,486,075.4	1,475,196.2	1,461,217.8	1,437,816.1
Lighting	161,113.5	147,979.3	129,850.0	108,601.0	86,429.1	63,403.5
Other appliances (vacuum cleaners, irons etc.)	1,320,209.2	1,337,322.9	1,356,225.3	1,366,595.2	1,374,788.7	1,374,412.6
Total number of appliances						
White appliances						
Refrigerators and freezers	281,386,019	291,932,612	304,497,583	316,257,646	329,569,096	342,024,030
Washing machine	183,768,546	190,087,533	199,158,165	209,279,726	219,587,016	232,061,615
Clothes dryer	64,612,619	68,086,186	71,170,754	73,924,700	77,176,183	81,093,406

- NB: Peak electricity consumption in Europe is around 500 GW.
- If all 1760 GW of appliances came on simultaneously, system would be overwhelmed.
- What do you notice about the ratio of total energy consumption to installed power?

EU28 - System efficiency indicator of total stock	2010	2011	2012	2013	2014	2015
Ratio of energy service to energy consumption	0.669	0.673	0.681	0.690	0.696	0.705
Space heating	0.675	0.679	0.686	0.696	0.702	0.712
Solids	0.512	0.513	0.514	0.516	0.517	0.519
Liquified petroleum gas (LPG)	0.641	0.647	0.654	0.662	0.666	0.672
Gas/Diesel oil incl. biofuels (GDO)	0.652	0.656	0.665	0.675	0.682	0.685
Gases incl. biogas	0.681	0.684	0.691	0.697	0.702	0.707
Biomass and wastes	0.542	0.545	0.550	0.556	0.559	0.564
Geothermal energy	0.820	0.830	0.837	0.840	0.848	0.851
Derived heat	0.805	0.808	0.810	0.822	0.824	0.831
Advanced electric heating	1.679	1.815	1.946	2.116	2.240	2.392
Conventional electric heating	0.787	0.791	0.798	0.807	0.808	0.815
Electricity in circulation	1.000	1.000	1.000	1.000	1.000	1.000
Space cooling	2.323	2.463	2.611	2.746	2.881	3.009
Air conditioning	2.323	2.463	2.611	2.746	2.881	3.009
Water heating	0.626	0.629	0.632	0.636	0.638	0.643
Solids	0.448	0.450	0.452	0.454	0.455	0.456
Liquified petroleum gas (LPG)	0.585	0.588	0.592	0.596	0.598	0.599
Gas/Diesel oil incl. biofuels (GDO)	0.570	0.572	0.577	0.580	0.584	0.586
Gases incl. biogas	0.589	0.591	0.595	0.598	0.600	0.604
Biomass and wastes	0.485	0.488	0.491	0.494	0.497	0.500
Geothermal energy						
Derived heat	0.847	0.850	0.850	0.855	0.858	0.860
Electricity	0.744	0.747	0.752	0.757	0.761	0.764
Solar	1.000	1.000	1.000	1.000	1.000	1.000
Cooking	0.615	0.620	0.624	0.628	0.632	0.638
Solids	0.344	0.345	0.346	0.347	0.348	0.349
Liquified petroleum gas (LPG)	0.461	0.463	0.466	0.469	0.470	0.472
Gases incl. biogas	0.505	0.508	0.510	0.513	0.515	0.518
Biomass and wastes	0.337	0.338	0.339	0.340	0.340	0.342
Electricity	0.839	0.841	0.843	0.846	0.848	0.850

- Ratio of final energy to actual heating for space/water/cooking.
- Which fuel source is most efficient?
- Why is 'air conditioning' efficiency greater than one?
- Why is 'advanced electric heating' efficiency greater than one?