Technische Universität Berlin

Energy Systems, Summer Semester 2021
Lecture 2: Energy Balances

Prof. Tom Brown
Department of 'Digital Transformation in Energy Systems', Institute of Energy Technology

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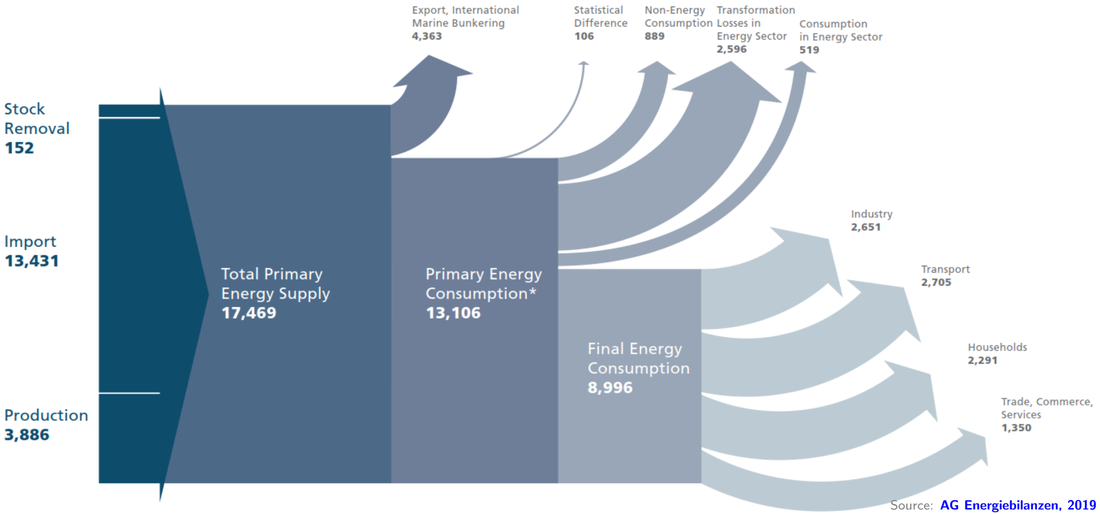
Measuring Energy

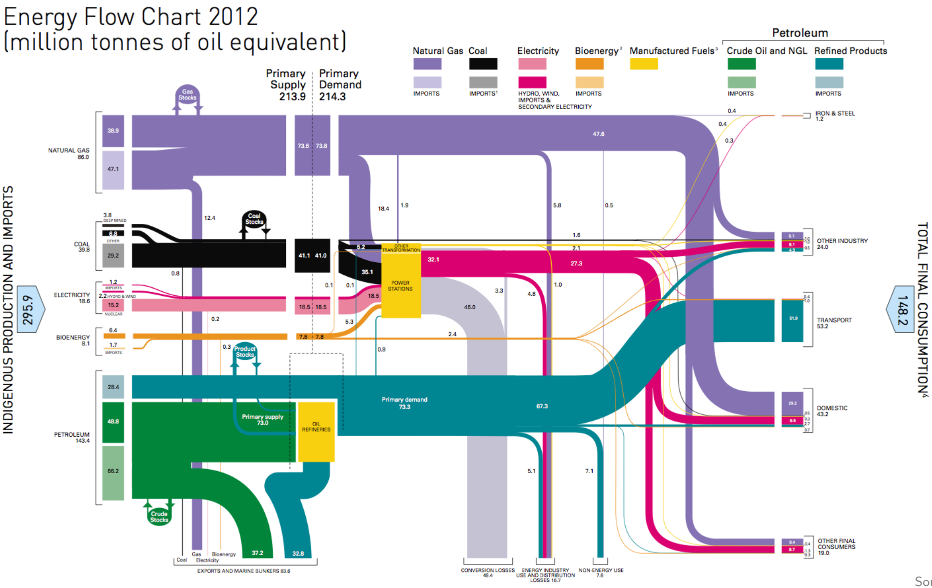
Goal: Understand Energy Flow Through the Economy

Example: energy flow chart for Germany in 2018 in Petajoule (PJ)



Source: AG Energiebilanzen, 2019

Example: UK in 2012



Source: BEIS, 2013

Energy conversion/transformation processes

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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

Source: Zweifel, Praktiknjo & Erdmann (2017)

Definitions: Primary Versus Final Versus Useful Energy

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**.

Units of Energy: Joule and tonne of oil equivalent

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 [m^3] to energy units using the **calorific value** [J/kg, J/m^3], 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: 41.9·10^9 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 ºC
1 t Gasoline	0.75 g/cm^3	43.1	at 15–20 ºC
1 t Methanol (CH_3OH)	0.80 g/cm^3	19.7	
1 t Ethanol (C_2H_5OH)	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 ºC
1 t Hydrogen (LH_2)	0.071 g/cm^3	120.4	at –252 ºC
1000 m^3 Natural gas L	0.82 kg/m^3	33.4	Mean: 35.6·10^9 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_3H_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· 10^9 J
1 t Lignite		7.5–13	
1 t Wood	0.6 g/cm^3	14.6	3.5 · 10^6 kcal
1 t Uranium oxide (U_3O_8)		414'000	Light Water Reactor LWR

Higher and Lower Heating Values

- **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.

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: Flow of energy

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 W = 1 J/s.

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

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

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

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

Power: Examples of consumption

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)?

Power: Supplying world's energy with wind and solar

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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 TW / 0.333 = 18 TW (around 743 GW was installed by 2020)

Solar: 6 TW / 0.166 = 36 TW (around 626 GW was installed by 2019)

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If installed wind density on average is 10 MW/km^2 and solar is 72 MW/km^2, what percentage of world land (510 million km^2) is taken with each?

Power: Supplying world's energy with wind and solar

If installed wind density on average is 10 MW/km^2 and solar is 72 MW/km^2, what percentage of world land (510 million km^2) is taken with each?

Wind: 18 TW/(10 MW/km^2) = 1.8 million km^2 (around 0.35% of total land = area of Indonesia)

Solar: 36 TW/(72 MW/km^2) = 0.5 million km^2 (around 0.1% of total land = area of Spain)

(NB: Wind doesn't interfere with other land uses like agriculture; solar can be rooftop or combined with agriculture = agrivoltaics.)

Units of energy: Watt-hour

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 W * 2 h = 20 Wh

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

1 kWh = (1000 W) * (1 h) = (1000 J/s)*(3600 s) = 3.6 MJ

Yearly energy to power

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

What is the *average* power consumption in GW?

Yearly energy to power

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

What is the *average* power consumption in GW?

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

Tables for converting units

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

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

Measuring primary energy of renewables

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

- **Substitution Principle:** (also know as the 'Input-Equivalent Method') (used by BP) amount of fuel that would be necessary to produce that amount of electricity in a thermal powerplant (35-45%)
- **Efficiency Principle:** actual efficiency of respective technology (hydro 80-90%, wind 30-55%, solar 10-25%)
- **Fictive Efficiency Principle:** (also known as 'Physical Energy Accounting Method' or 'Direct Equivalent Method') (most common: used by IEA, OECD, Eurostat, IPCC) assume 100% efficiency of primary energy to electricity for wind, solar, hydro

Beware: primary energy can underestimate renewables share

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 from renewables:

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

Beware: primary energy can underestimate renewables share

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 from renewables:

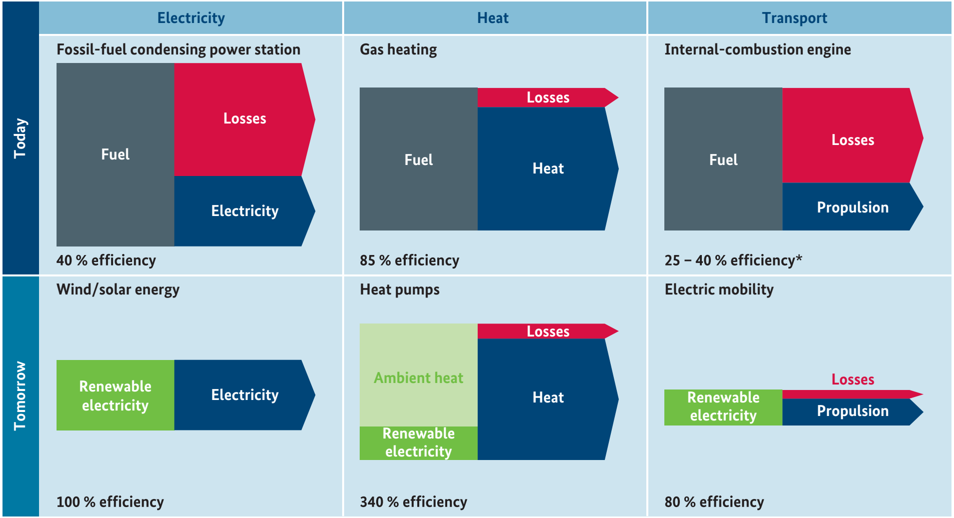
1. Using the Substitution Principle
2. Using the Fictive Efficiency Principle

1. 50% (since we assume renewables need as much primary energy for each unit of electricity as a thermal plant)
2. $\frac{50}{50+50/0.33}\% = \frac{50}{50+150}\% = 25\%$

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.



Source: BMWi White Paper 2015

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

Primary and final energy change with renewables and electrification

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 decline** (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 will decline! Primary by $\sim 50\%$, final by $\sim 33\%$.

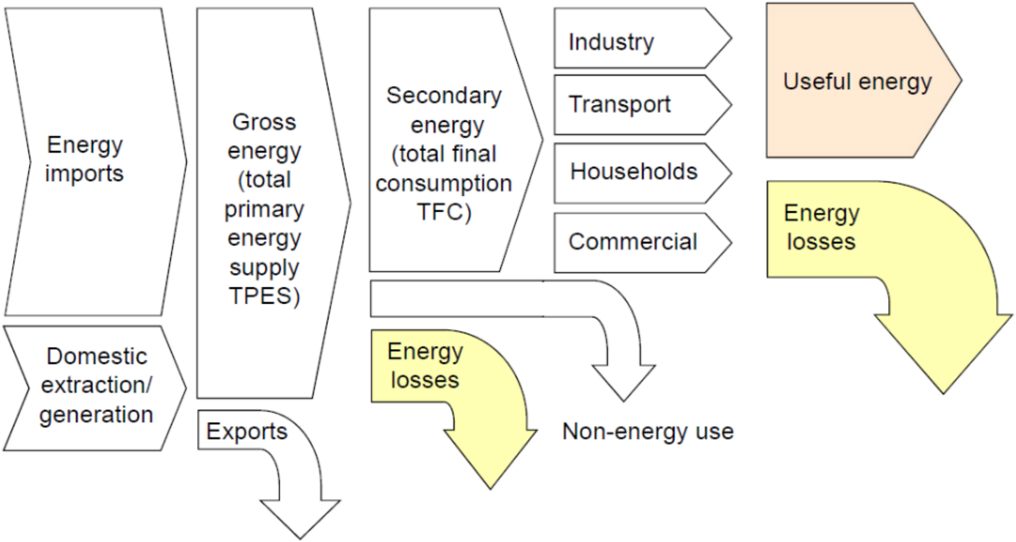
Expect roughly **double electricity demand** (assuming widespread electrification of end demands, indirect electrification with H2 and efficiency measures).

Electricity will become the dominant final energy, primary energy will become less relevant.

Most important metric becomes: fraction of electricity from non-emitting sources.

Energy Balances

Principles of Energy Flow



Source: Zweifel, Praktiknjo & Erdmann (2017)

Energy Flow In Germany

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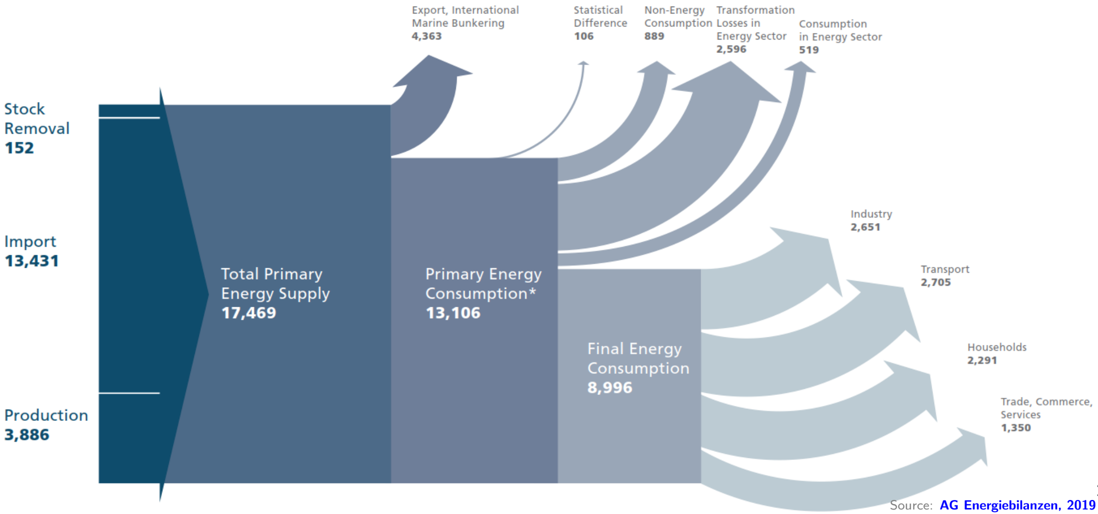
Example: energy flow chart for Germany in 2018 in Petajoule (PJ)



Source: AG Energiebilanzen, 2019

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	B_100100	755,389	131,850	74,354	107,238	210,708	14,537	216,703		
+ Primary production receipt	B_100110	9,397		9,397						
+ From other sources (Recovered products)	B_100200	4,522	404	3,818	300					
+ Recycled products	B_100210	1,044		1,044						
+ Imports	B_100300	1,483,219	134,902	941,564	357,102	16,395	385		6	32,865
+ Stock changes	B_100400	21,263	11,807	3,423	5,944	89	0			
- Exports	B_100500	579,508	38,239	411,746	87,613	10,574	29		5	31,301
- Bunkers	B_100800	44,152		44,151	1					
- Direct use	B_100112	10,559		10,559						
Gross inland consumption	B_100900	**1,640,615**	**240,724**	**567,142**	**382,969**	**216,618**	**14,893**	**216,703**	**1**	**1,564**
Transformation input	B_101000	**1,294,958**	**224,492**	**654,689**	**125,132**	**61,875**	**11,027**	**216,703**	**768**	**272**
+ Conventional Thermal Power Stations	B_101001	358,478	165,433	12,820	114,576	54,977	9,905		768	
+ Nuclear Power Stations	B_101002	216,703						216,703		
+ Coke-ovens	B_101004	36,597	36,215	355	27					
+ Blast-furnaces	B_101006	12,918	12,918							
+ Gas works	B_101007	695	674		21					
+ Refineries	B_101008	640,308		640,308						
+ District heating plants	B_101009	21,015	3,544	963	8,654	6,459	1,122			272
+ Patent fuel plants	B_101010	219	142	77						
+ BKB / PB Plants	B_101011	4,385	4,385							
+ Coal Liquefaction Plants	B_101012	901	901							
+ For Blended Natural Gas	B_101013	391		162		230				
+ Charcoal production plants (transformation)	B_101015	209				209				
+ Gas-to-Liquids (GTL) Plants (transformation)	B_101016									
+ Non-specified Transformation Input	B_101020	2,138	279	4	1,855					
Transformation output	B_101100	**963,032**	**31,378**	**640,125**	**20,223**	**62**			**59,192**	**212,054**
+ Conventional Thermal Power Stations	B_101101	181,172							41,319	139,854
+ Nuclear power stations	B_101102	72,303							103	72,200
+ Coke-ovens	B_101104	34,193	27,365		6,828					
+ Blast-furnaces	B_101106	12,918			12,918					
+ Gas works	B_101107	477			477					
+ Refineries	B_101108	640,125		640,125						
+ Patent Fuel Plants	B_101110	173	173							
+ BKB / PB Plants	B_101111	3,840	3,840							
+ Charcoal production plants	B_101115	62				62				
+ District Heating Plants	B_101109	17,770							17,770	
Exchanges and transfers, returns	B_101200	**2,969**		**2,969**		**-65,240**				**65,240**
Consumption of the energy branch	B_101300	**80,128**	**636**	**33,402**	**19,028**	**654**	**87**		**4,913**	**21,408**
Distribution losses	B_101400	**26,372**	**35**	**53**	**3,093**	**24**			**5,554**	**17,612**
Available for Final Consumption	B_101500	**1,205,158**	**46,938**	**522,093**	**255,939**	**88,886**	**3,780**		**47,957**	**239,565**
Final non-energy consumption	B_101600	**97,773**	**1,763**	**82,480**	**13,530**					
Final energy consumption	B_101700	**1,107,818**	**45,338**	**437,131**	**245,284**	**88,949**	**3,780**		**47,932**	**239,405**
+ Industry	B_101800	276,823	33,774	27,513	86,242	22,542	3,524		16,112	87,115
+ Transport	B_101900	367,272	12	344,648	3,284	13,840				5,488
+ Other Sectors	B_102000	463,723	11,552	64,969	155,758	52,567	256		31,820	146,801
+ Services	B_102035	150,043	923	15,668	46,281	4,889	255		9,274	72,754
+ Residential	B_102010	284,832	9,507	33,139	105,175	45,369			22,148	69,494
+ Agriculture / Forestry	B_102030	24,079	1,082	12,992	3,426	2,132	1		252	4,194
+ Fishing	B_102020	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

Source: Eurostat Energy Balances

Questions

- 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?

Moving Beyond Energy Balances: JRC IDEES Database

Includes more granular estimates of useful energy, efficiency, CO_2 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?

Source: JRC IDEES

JRC IDEES: Residential heating efficiency

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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?

Source: JRC IDEES