The Incredible Inefficiency of the Fossil Energy System

ARTICLE

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Today's fossil energy system is incredibly inefficient: almost two-thirds of all primary energy is wasted in energy production, transportation, and use, before fossil fuel has done any work or produced any benefit. That means over $4.6 trillion per year, almost 5% of global GDP and 40% of what we spend on energy, goes up in smoke due to fossil inefficiency. Literally.

The winds are changing, though, as fossil technologies are undercut by more efficient alternatives. End-use efficiency is driving out fossil fuels, reinforced by three new tailwinds that upend the energy landscape: renewable electricity, localization, and electrification. These drivers will allow us to drastically cut down on energy waste and phase out fossil fuels.

Summary

- **Today's energy system is incredibly inefficient.** We waste almost 400 exajoule (EJ) of all energy going into our energy system (two-thirds of total), worth over $4.5 trillion, or almost 5% of global GDP — all before any value is created with energy.
- **The main culprit is the widespread use of fossil fuels**. The majority of energy losses are driven by the inherent inefficiencies of producing and delivering fossil fuels (177 EJ per year), transportation (19 EJ per year), and use (183 EJ per year).
- **The standout waste is from fossil fuel power plants and Internal Combustion Engines (ICEs)**. These two technologies combined are responsible for almost half the energy waste globally.
- **Fossil inefficiency is fossil fragility.** Inefficient energy use is vulnerable to more efficient alternatives, as competition by more efficient solutions can deliver more or better services, more conveniently, at lower cost.
- **We have seen this before**. Fossil fuel technologies themselves rose to prominence a century ago through competing on efficiency, pushing out less efficient technology and fuels along the way.
- **It is happening again.** Both more efficient end-use and new clean supply technologies – solar, wind, heat pumps, electric vehicles, and many more – all undercut fossil fuels where they are at their weakest: rampant inefficiency.

The drivers of energy waste

The journey of a unit of energy through the global system passes through five key stages. Initially, it is extracted as *primary energy* — such as coal and crude oil from the earth. This energy is then processed into *final energy* that can be used more easily, such as gasoline and electricity, which is transported and sold to end-users. These users convert this final energy into *useful energy* through devices like boilers and engines, turning the final energy captured in fuels into functional forms such as hot water or a moving vehicle. This useful energy delivers *energy services* across society, such as heating a home or transporting goods. Finally, energy services are used to *create value and prosperity* for the consumer — comfort, mobility, and illumination — turning energy into an improvement in prosperity, quality of life, and human satisfaction and happiness.

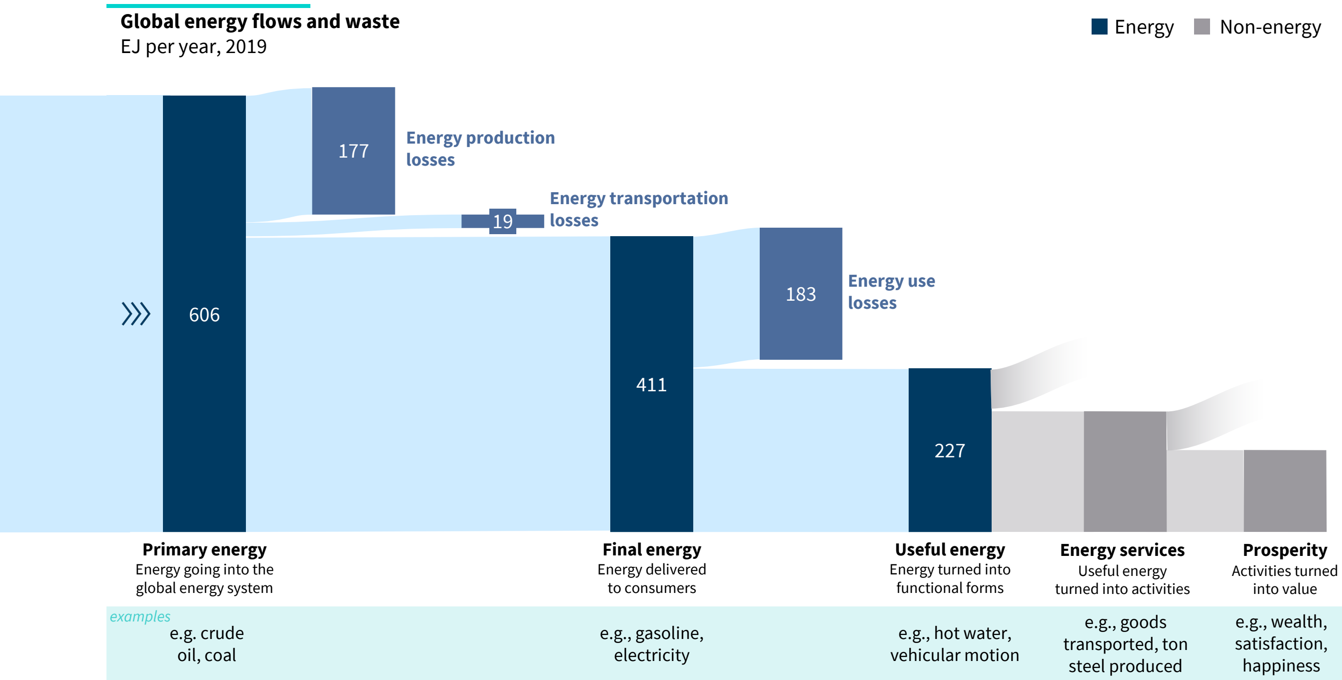
Today, most energy is wasted along the way. Out of the 606 EJ of primary energy that entered the global energy system in 2019, some 33% (196 EJ) was lost on the supply side due to energy production and transportation losses before it ever reached a consumer. Another 30% (183 EJ) was lost on the demand side turning final energy into useful energy. That means that of the 606 EJ we put into our energy system per annum, only 227 EJ ended up providing useful energy, like heating a home or moving a truck. That is only 37% efficient overall.

How big is an Exajoule?

1 EJ roughly equals the annual energy consumption of New York City

As we will examine in a subsequent piece, total efficiency is in fact even lower because there are losses between useful energy and energy services and between energy services and prosperity. For instance, some 30% of construction material — steel, concrete, etc. — is wasted on a typical construction site globally.[1] In the United States, some 35% of truck miles are driven empty to new pick-up locations, which could largely be eliminated with better logistics.[2]

Exhibit 1: Energy system losses from primary to useful, 2019



Source: IEA, RMI analysis

In financial terms, as explained in more detail in the Appendix, the loss of 379 EJ per year means we waste some $1 trillion per year in energy spending on the supply side, and another $3.6 trillion on the demand side. That adds up to $4.6 trillion per year, which averages out to about $600 wasted annually per person globally. This represents 40% of total global spending on energy, or about 5% of global GDP, which is roughly double the annual investments into the energy system every year.[3]

Energy production losses

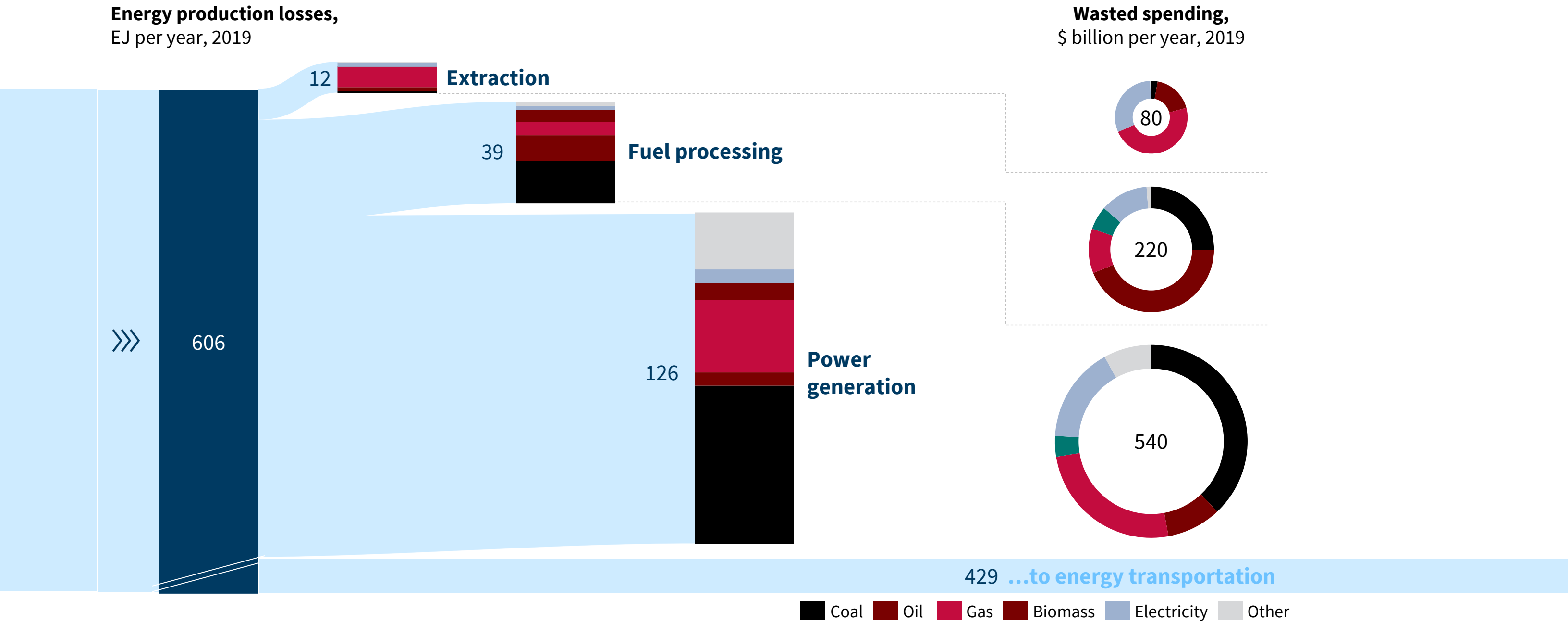
It takes energy to make energy. The three key drivers of energy waste in production processes are extraction (getting raw fuels out of the ground), fuel processing losses (turning raw extracted fuels into ready-for-use molecules) and power generation losses (turning molecules into electrons).

Power generation drives the largest loss by far: 126 EJ per year, worth about $540 billion. Thermal losses of coal and gas power plants make up the majority of this energy waste: about 60 EJ per year from coal and 30 EJ per year from gas power generation.

Other losses derive mostly from fossil extraction and processing steps such as oil refineries, coal mines, and gas extraction. This wastes another 51 EJ worth $300 billion per year.

As raw fuels are upgraded into useful forms, they become more valuable, so a unit of energy lost in production has a lower monetary value than a unit of final energy lost later or a unit of waste in useful energy and delivered energy services.

Exhibit 2: Energy production waste, 2019



Source: IEA, RMI analysis

Energy transportation losses

A smaller but not insignificant 19 EJ per year is lost in transporting energy from supply to demand centers. This corresponds to wasting some $200 billion per year.

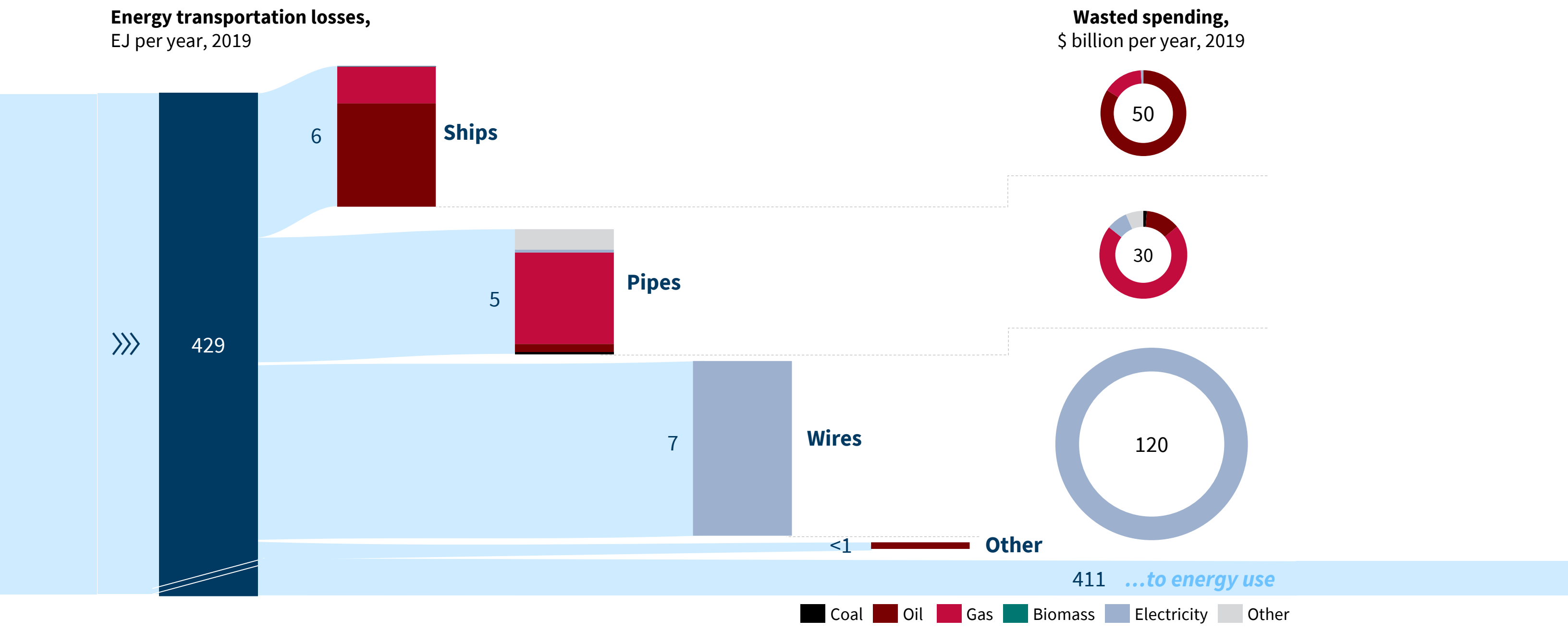
The three key drivers of waste in transportation are energy losses in ships, pipes, and wires.

Ship losses are mostly driven by the energy consumption of vessels that transport fossil fuels around the world and the liquefaction and regasification for Liquefied Natural Gas (LNG) transport. According to Rystad, some 45% of total shipping demand is for transporting fossil fuels.[4] That means some $42 billion per year is spent on fossil shipping fuels to transport other fossil fuels to their point of use. Another $8 billion per year is wasted on liquefaction and regasification for LNG transport. Note that these figures only include spending for energy used to transport other energy — not including the sizable costs of the ships, crew, and port infrastructure themselves.

Pipe losses comprise the energy used to transport methane gas, crude oil, liquid fuels made from them, and some coal transported in slurry pipelines — mainly to run pumps and compressors and to make up for leaks throughout the vast wholesale and retail distribution networks. That use exceeds $30 billion of lost value per year.

In energy terms, pipes and wires lose a comparable amount of energy (5 vs 7 EJ), but as wires transport more valuable electricity, the total wasted spending from wire losses is almost five times as much as from pipe losses.

Exhibit 3: Energy transportation losses



Source: IEA, RMI analysis

Energy use losses

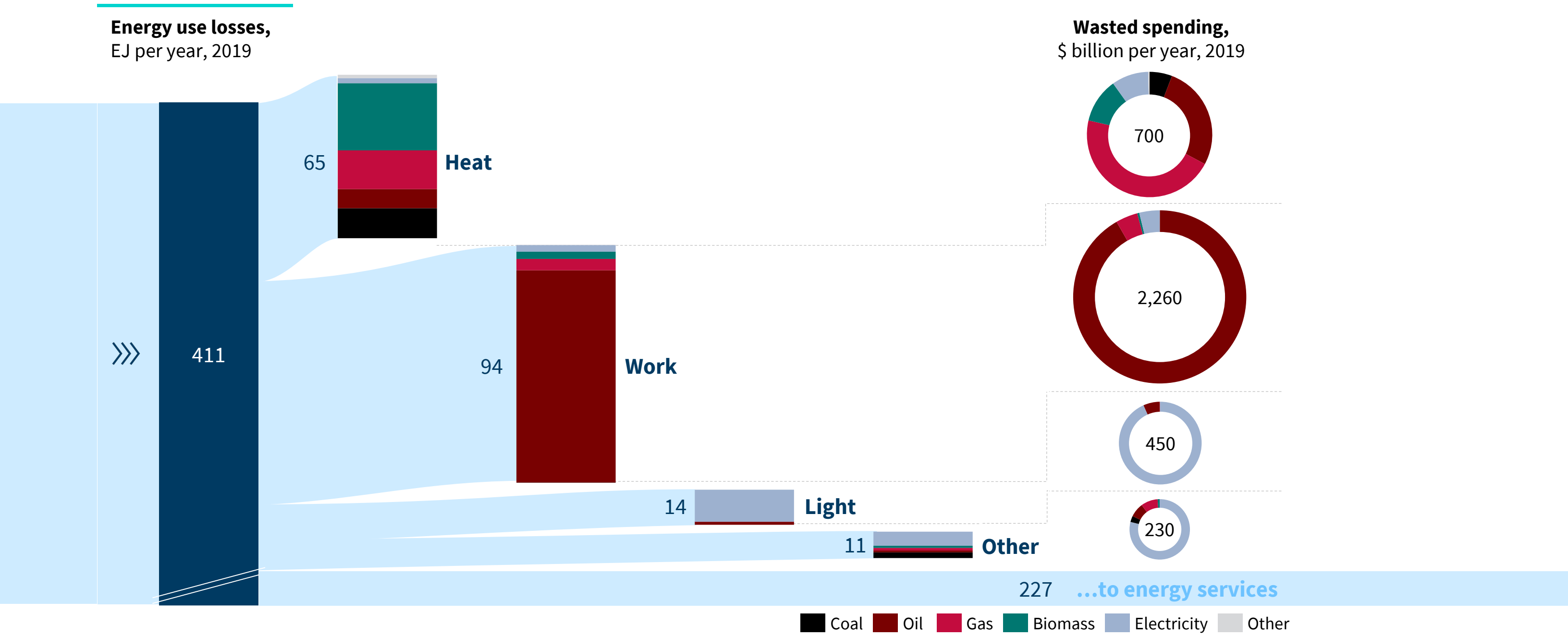
Most energy is used to provide one of three core energy services: producing heat (for water or air heating in buildings or heating in industry), doing work (mostly in transport — engines that power cars and buses — but also driving things like conveyor belts in factories), or generating light (to allow for activity after dark or in dark interiors). Each comes with its own losses.

Heat and work production are the main drivers of waste — light generation is already largely electrified, and the rising share of LED lightbulbs will further reduce losses.

Heat losses account for some 65 EJ per year. Some 40% is driven by the inefficient use of biomass for heating and cooking in lower-income countries. The associated wasted spending is small compared to more costly losses of oil and gas in heating, as biomass is a cheap fuel. Fossil losses account for over $550 billion per year, while biomass is less than $50 billion.

Work losses are even larger: 94 EJ per year is wasted turning (mostly fossil) fuels into work. The vast majority of waste comes from oil combustion in Internal Combustion Engines (ICEs), providing the work that drives our cars, trucks, and buses. Some $2 trillion per year is wasted in ICEs that are less than 25% efficient on average. Other work losses from stationary machinery already use more efficient energy carriers, like electricity, so losses are smaller.

Exhibit 4: Energy use losses



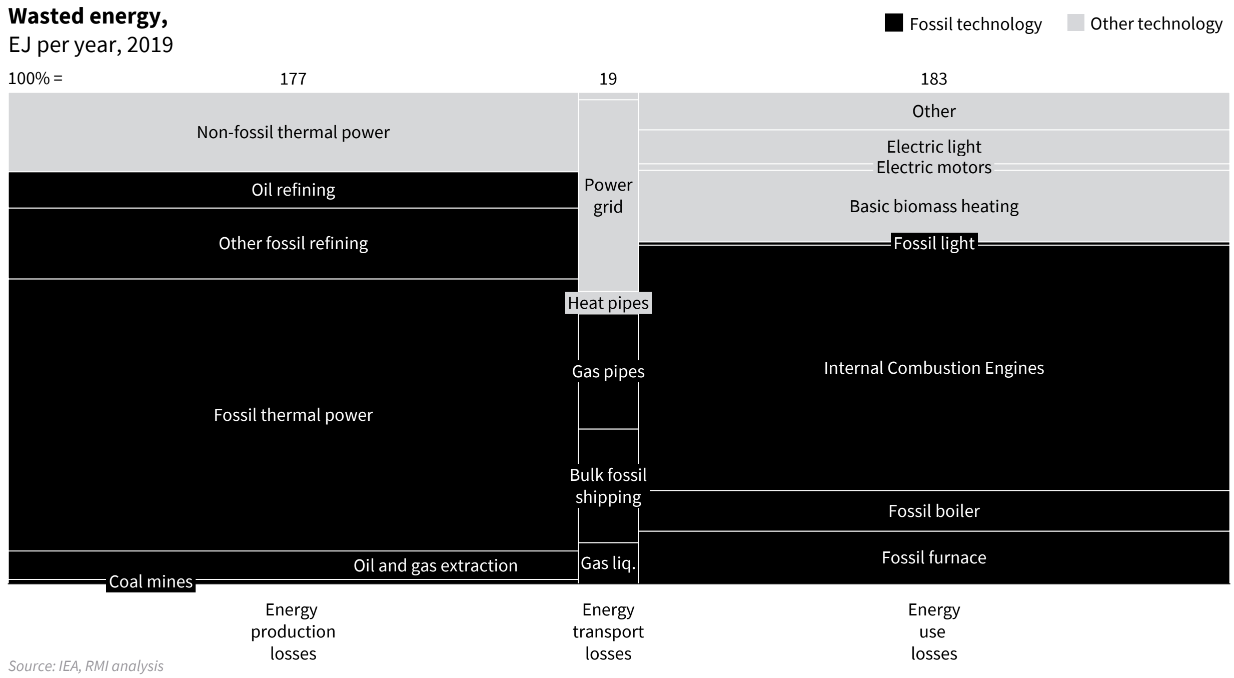
Source: IEA, RMI analysis

Fossil technology drives losses throughout

Across production, transportation, and use, fossil technologies are the main drivers of energy waste: over 75% of energy losses are directly attributable to fossil technologies, as shown below. The standouts are fossil thermal power plants and ICEs. These two technologies combined are responsible for almost half the energy waste globally.

Fossil technology not only wastes a lot of energy, it also produces a lot of other waste byproducts. The use of fossil fuels emits 35 of the total 37 gigatons (Gt) of CO_2 emitted per year, and is responsible for another 3 $GtCO_2e_{100}$ in methane emissions. Other wastes, such as particulate matter emissions, responsible for over 5 million deaths per year, are also directly attributable to fossil technology.[5]

Exhibit 5: Energy losses by technology group



Source: IEA, RMI analysis

Fossil inefficiency is fossil fragility

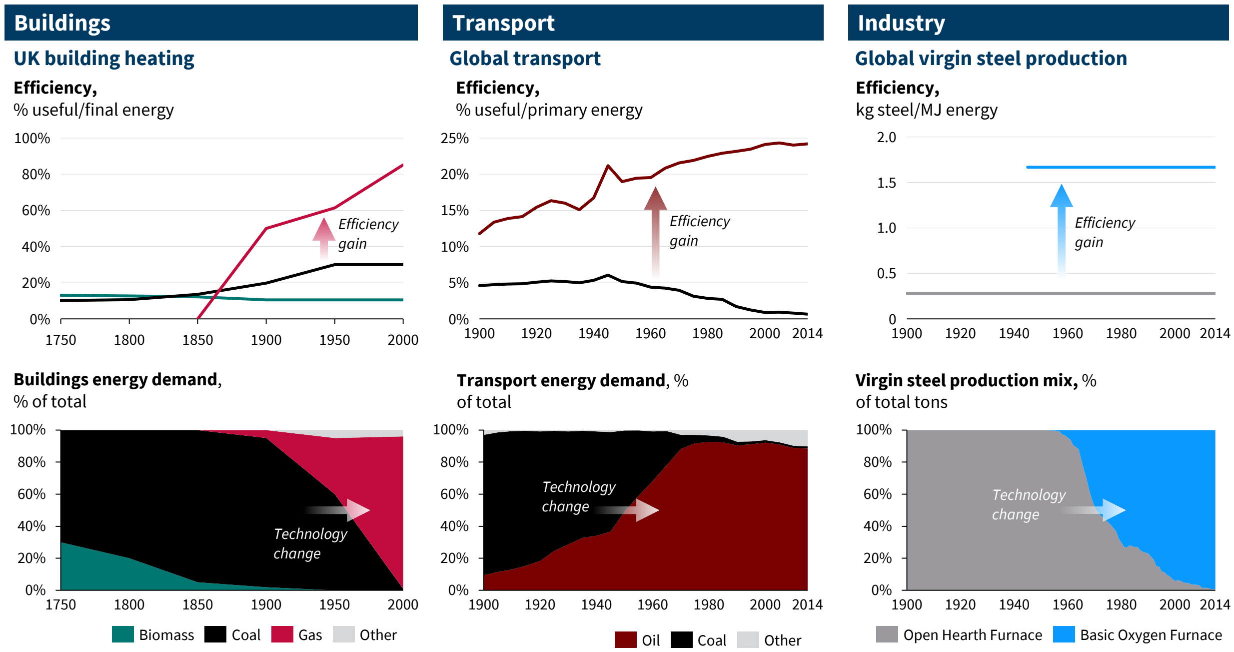
The fossil system's incredible wastefulness is partly by design. For a century, the global economy primarily prioritized energy *volume*-add, not *value*-add — investing into boosting energy sales, not the value each unit of energy adds. As the international Energy Agency (IEA) shows, less than 11% of total annual energy investments went to energy efficiency in the past five years, while some 90% went toward energy volume additions. [6] We invest mostly in energy quantity, not quality and efficiency.

This strategy has led to a ballooning energy system, fueling super profits for the fossil fuel industry over the past century. It also led to rampant inequities, and a world where over 60% of energy goes to waste while some hundreds of millions live in energy poverty,[7] and we experience global energy shocks every two to three decades.[8] At the same time, the fossil fuel industry is rewarded with economic rents of $1–$2 trillion every year as well as over $7 trillion in subsidies (2 and 7% of global GDP respectively).[9]

But this strategy has also made the fossil fuel industry increasingly vulnerable. Inefficient fuels can be outcompeted by leaner, more efficient alternatives. This very dynamic drove the success of fossil fuels over the past 150 years, as coal, oil, and gas first outcompeted biomass and then vied with each other by being more efficient and cost-effective, and allowing for more sustainable growth.[10] Some examples are shown below: in the UK, more efficient coal outcompeted biomass, and then more efficient gas outcompeted coal. In global transport, more efficient oil outcompeted coal. And in steel, more efficient basic oxygen furnaces outcompeted open hearth furnaces.

This will happen again. There is a target on the back of the fossil system, worth ~400 EJ in energy and over $4.5 trillion in sales per year. More efficient alternatives are finding inroads to capture this value and push out fossil fuels.

Exhibit 6: Historical technology energy efficiency and share of total



Source: Fouquet 2008; IIASA; Wang, Ryburd et al. 2021

The winds of change

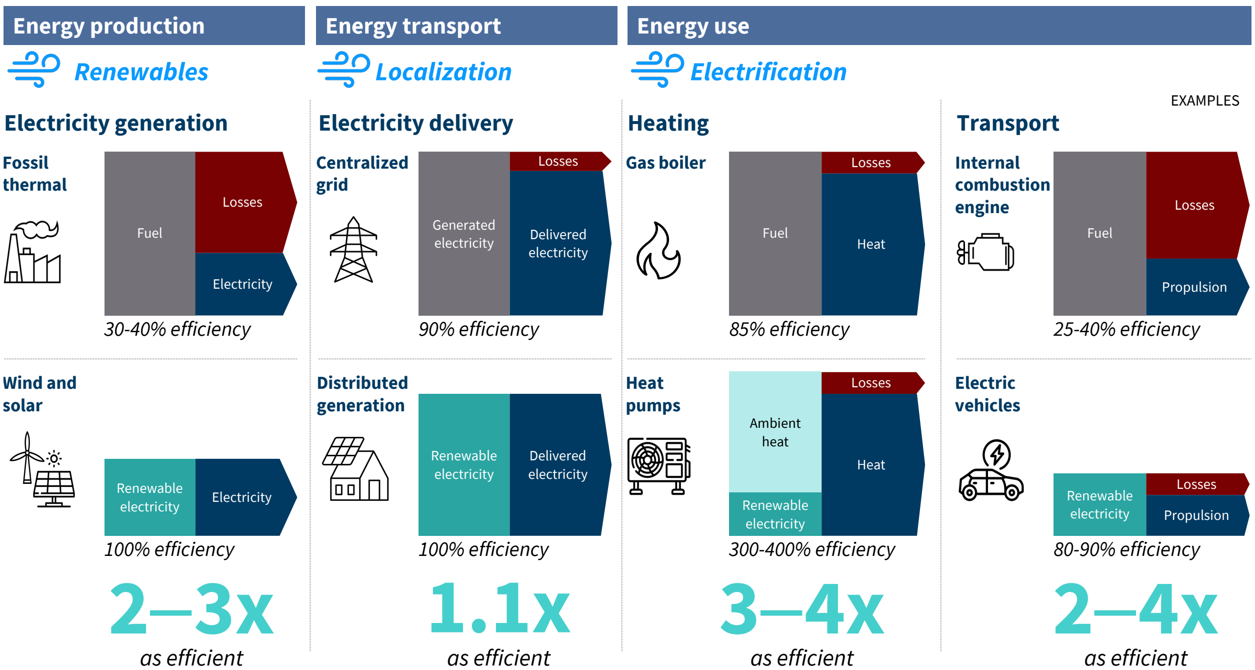
There are many solutions that curtail the inefficiency of the fossil fuel system, as analyzed by the IEA[11] and many others[12] in detail. They can roughly be divided into two types: energy transformation efficiency (improving the efficiency of transforming primary to useful energy), and end-use efficiency (lowering the amount of useful energy needed to provide energy services and create value).

Global system energy efficiency gains (GDP growth minus primary energy demand growth) have been on average 1.5% per year since 2000, driven mainly by end-use efficiency gains, such as by better air conditioners and LED lights, system approaches such as redesigning cities, improving product and building design, but also simply pursuing more economic growth through services instead of energy-intensive manufacturing. As the IEA points out, the rate of end-use efficiency gains can easily and cost-effectively double, if not triple, with the right policy support.[13]

On top of end-use efficiency gains, three new energy transformation changes will have outsized impact on the energy system this decade. Three tailwinds are picking up that will boost system efficiency gains:

- **Renewables.** Wind and solar energy can be generated almost entirely without losses as they require effectively no extraction or processing energy, nor suffer major thermal losses like fossils.
- **Localization.** Locally generated renewables eliminate the need to ship and pipe fuels around the world, and, where possible, distributed generation of electricity at the point of demand (e.g., rooftop solar) avoid the need to transport energy altogether.
- **Electrification.** Technologies such as heat pumps and electric vehicles eliminate most wasted energy in producing heat and work and are two to four times more efficient than natural gas boilers or ICEs respectively.

Exhibit 7: Fossil technology versus clean tech alternative across the energy system



IEA, IIASA, RMI analysis, Visual adapted from Prof. Tomas Kåberger

As in the historical examples shown in Exhibit 6, the efficiency gains of these new technologies over fossil incumbents result in a competitive advantage. Despite typically coming at higher up-front cost, the total lifetime cost of these alternatives tends to lie well below that of the incumbent fossil technology. As explored in our X-Change series, these technologies are all on S-curves today and growing exponentially.[14]

As they pick up, the supply side of the energy system will become significantly more efficient.

The rapid uptake of these technologies can be a key driver of more demand-side efficiency gains as well. Installing a new heat pump is the perfect time for households to consider additional building envelope retrofits such as insulation: enough insulation can shrink if not eliminate the heat pump. When engineers design new EVs, better aerodynamics and lightweighting are essential to improve range and save batteries. As an industrial site undergoes a major retrofit to switch to heat pumps, new pipe designs with less friction (fatter, straighter pipes) or other more efficient process designs can be implemented. The exponential uptake of renewables, localization, and electrification hence also means an exponential increase in potential intervention moments for designers and end users to consider demand-side efficiency opportunities.[15]

In upcoming research, we aim to explore these drivers of change in more detail.

Conclusion

Incredible inefficiency means a remarkable opportunity for disruption worth two-thirds of all energy demand and $4.6 trillion per year. Efficiency lies at the core of the energy transition to come, as was the case in energy transitions before. It should not merely be seen as one driver out of many but as an essential catalyst driving competitiveness, sustainability, and availability of all new clean technologies and systems.

As the winds of change pick up, efficiency emerges as the deciding transition force in the decades to come.

Endnotes

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[1] Mohamed Osmani, 2011, https://www.sciencedirect.com/topics/earth-and-planetary-sciences/construction-waste

[2] "Logistics sector mulls how to keeping on trucking in a net-zero future", Reuters, 2023, https://www.reuters.com/sustainability/boards-policy-regulation/logistics-sector-mulls-how-keeping-trucking-net-zero-future-2023-06-12/

[3] World Energy Investment 2023, IEA https://www.iea.org/reports/world-energy-investment-2023

[4] Rystad Global Energy Scenarios 2023, Rystad, p 122 https://www.rystadenergy.com/flagship-report-energy-transition

[5] Lelieveld et al., 2023, BMJ 2023;383:e077784, https://www.bmj.com/content/383/bmj-2023-077784

[6] IEA WEI 2023 and Energy Efficiency report, https://www.iea.org/reports/world-energy-investment-2023/overview-and-key-findings; https://www.iea.org/reports/world-energy-investment-2020/energy-end-use-and-efficiency

[7] IEA Energy Access tracker, 2023 https://www.iea.org/topics/energy-access

[8] There have been four global energy shocks the past 50 years alone: 1973, 1979, 1990, and most recently 2021 following COVID and Putin's invasion of Ukraine. There have been dozens of local energy crises over the same time period — see for example Thunder Said's overview https://thundersaidenergy.com/downloads/energy-crises-an-overview-from-history/

[9] World Bank fossil rents database 2023 https://data.worldbank.org/indicator/NY.GDP.PETR.RT.ZS https://data.worldbank.org/indicator/NY.GDP.COAL.RT.ZS ; IMF, 2023, https://www.imf.org/en/Blogs/Articles/2023/08/24/fossil%2Dfuel%2Dsubsidies%2Dsurged%2Dto%2Drecord%2D7%2Dtrillion

[10] Heat, Power and Light: Revolutions in Energy Services, Fouquet, 2008

[11] Energy efficiency 2023, IEA, 2023. https://iea.blob.core.windows.net/assets/dfd9134f-12eb-4045-9789-9d6ab8d9fbf4/EnergyEfficiency2023.pdf

[12] For example, see the overview in Energy efficiency, Fawkes, 2013

[13] Energy Efficiency 2023, IEA, 2023, https://www.iea.org/reports/energy-efficiency-2023

[14] X-Change Electricity, X-Change Cars, X-Change Batteries, RMI, 2023, https://rmi.org/insight/x-change-electricity/; https://rmi.org/insight/x-change-cars/; https://rmi.org/insight/x-change-batteries/

[15] For instance, see the RMI ZOT approach, https://rmi.org/insight/zero-over-time-for-building-portfolios/#:~:text=A%20zero-over-time%20(,cycle%20events%2C%20like%20equipment%20upgrades