ENERGY AND ENVIRONMENT PARTNERSHIP / SOUTHERN AND EAST AFRICA

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**PHASE II**

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# TECHNICAL BRIEF

## ENERGY EFFICIENCY GENERAL

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*This technical brief is published by the Energy & Environment Partnership programme to provide technical background on the concept on energy efficiency.*
*This brief will assist in understanding energy efficiency and its importance in the energy chain.*

# 1. BASIC DEFINITIONS

In its basic definition, energy efficiency (EE) describes the ratio between a system's energy input and energy output. Practical evaluation of EE encompasses many real-world considerations, which are not necessarily limited to a direct comparison of input-output energy ratios. In general, all energy efficient processes or practices aim to reduce the amount of energy that is not used or lost by the system. Mathematically, EE can be defined as follows:

EE = Useful Energy Out/Total Energy In

EE is expressed as a percentage, which is
- in relation to input energy, or
- in relation to an industry standard control.

Any system that produces, transports, stores or consumes energy has some form of energy efficiency. The table below provides an overview of EE performance for generalized power-related systems.

It is important to distinguish between energy efficiency and yield:

1. From the table bellow, a typical wind system has an efficiency of between 35-45%, depending on the construction of the system, generator efficiency, and on the control systems involved to manage the performance of the wind turbine. If a steady wind is blowing at an air velocity that is within the performance curve of the wind turbine, 35-45% of the kinetic energy in the air current will be converted into electrical energy.

2. However, the wind turbine's energy yield over time is affected by the stochastic nature of wind speed. The yield of a wind turbine will be much lower than the actual efficiency of the system, due to the fact that the primary power source (wind) is intermittent and variable.

| Device or system | Description | Efficiency |
|---|---|---|
| Most efficient coal-fired power station in the world. | Trianel Kohlekraftwerk Lünen, Germany.[1,2] | 46% |
| Typical coal-fired power station | More than 80% of all traditional coal-fired power plants in the world.[3] | 25-37% |
| Wind power | Typical wind turbine.[4] | 35-45% |
| Solar panel | Typical photovoltaic panel's conversion from solar radiation to electrical energy.[5] | 13-22% |
| Vehicle with internal combustion engine | The amount of energy that is converted from fuel in the engine to torque on the wheels of the vehicle.[6] | 25% |
| Electric vehicles | Energy to charge the vehicle's batteries compared to energy used to propel the vehicle.[7] | 60% |
| Human body | Efficiency of converting food energy into mechanical output in the muscular system.[8] | 25% |

Table 1: Examples of EE are illustrated in this table

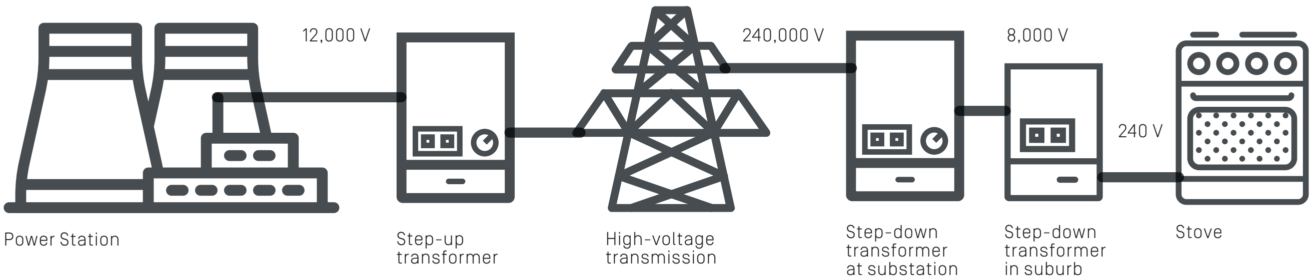
1 trianel-luenen.de
2 power-technology.com/projects/lnen-coal-fired-power-plant
3 ABB Report; The state of global energy efficiency; abb-energyefficiency.com
4 pg 2; Wind Turbine Power Calculations; The Royal Academy of Engineering
5 energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film
6 US Dept of Energy; fueleconomy.gov; fueleconomy.gov/feg/atv.shtml
7 fueleconomy.gov/feg/evtech.shtml
8 physics.stackexchange.com/questions/46788/how-efficient-is-the-human-body

# 2. ENERGY EFFICIENCY OF A SYSTEM

Energy efficiency is especially prevalent in complex energy transfer systems. The total efficiency of a system is the product of the efficiencies of all the respective sub-systems. The following example serves to illustrate the concept:

## 2.1. HYPOTHETICAL EXAMPLE: COAL-FIRED ELECTRICAL GRID

The approved Way Forward strategy including the £4.5 million of additional funding from DFID gave a much needed injection of funds to the EEP Programme. The application processes of the latest Call for Proposals (CfPs) 12 and 13 were implemented with updated content and a fresh online application portal.




**Assume the following sub-system efficiencies for the system above:**

1. Coal power station: 35%
   This means that only 35% of the chemical energy in coal is transferred to electrical energy. The rest of the energy is lost mostly as heat.

2. Step-up transformer: 95%
   About 5% of the energy is typically lost as heat during voltage conversion.

3. Transmission line: 95%
   This means that 5% of the energy is lost as heat due to the resistance of the entire transmission line.

4. Step-down transformer: 95%
   This means that 5% of the energy is typically lost as heat during voltage conversion.

5. Household appliance - Stove: 90%
   In this example, 90% of the electrical energy is transferred into heating the pot. The remainder of the heat escapes to the environment around the pot.

The energy transfer for heating the pot on the stove is explained in the table below:

| Stage | Efficiency of stage | Efficiency after stage |
|---|---|---|
| Coal fuel | n/a | 100,00% |
| Power plant | 0,35 | 35,00% |
| Transformer | 0,95 | 33,25% |
| Transmission line | 0,95 | 31,59% |
| Transformer | 0,95 | 30,01% |
| Stove | 0,85 | 25,51% |

Table 2: Sub-system efficiency and energy transfer

For this typical example, only 25,5% of the energy that is contained in the coal is actually transferred to the pot on the stove. The rest of the energy is mostly lost from the system as heat.

## 2.2. IMPORTANCE OF DOWNSTREAM ENERGY EFFICIENCY IMPROVEMENTS

Consider the situation where the stove at the end of the energy supply chain becomes only 1% more efficient, meaning that 1% more energy is transferred to the cooking pot instead of being lost to the environment. If in both cases, the same amount of energy/power must be transferred to the cooking pot, the upstream impact of 1% saving is as follows:

| Power transfer: | 85% efficient stove [Watts] | 86% efficient stove [Watts] |
|---|---|---|
| From stove to pot | 1000,00 | 1000,00 |
| Stove | 1176,47 | 1162,79 |
| Step-down transformer | 1238,39 | 1223,99 |
| Transmission line start | 1303,57 | 1288,41 |
| Step-up transformer | 1372,18 | 1356,22 |
| Power plant | 3920,51 | 3874,92 |

Table 3: Effect of 1% improvement of energy efficiency on the end use, assuming 1kW transfer to the cooking pot

In this example where 1kW has to be transferred to the cooking pot, a 1% saving in efficiency will lead to 13,7W savings at the end-use appliance, but to 45,6W being saved upstream.

*The above example serves to illustrate how small EE improvements on the downstream side has compounded savings upstream.* The idea that downstream savings merit the greatest emphasis is essential to optimizing the energy efficiency of a complex system.[9]

[9] pg 122; Chapter Six: Tunneling Through the Cost Barrier; Natural Capitalism; A Lovins; 1999; NC-99-06

# 3. METHODS FOR IMPROVING ENERGY EFFICIENCY

## 3.1. EFFICIENT DESIGN

Efficient design relies on altering a system in such a way that the energy efficiency of the system is improved without fundamentally altering the technology. This type of approach relies on an understanding of the system performance and avoidable energy losses, and offers low-hanging fruits for EE improvements.

Examples of efficient design for improved EE:

1. The heating and cooling budget on a house in the Southern Hemisphere can be significantly reduced if the structure is oriented with large North-facing windows with overhanging awnings. This optimizes the influx of sunlight during cold winter months, and shields sunlight during the summer.

2. The aerodynamics of box-shaped trucks can be improved by streamlining the design of the vehicles or by closing truck and trailer gaps in such a way that less turbulence is created.

3. By avoiding right-angled bends in piping systems, the flow resistance of a system can be optimized so that smaller pumps are required, thereby saving energy.

## 3.2. IMPROVED TECHNOLOGY

Energy efficiency can be achieved by altering the technology that is used to achieve a desired outcome. In many cases, an improvement in technology is due to an advancement in material sciences or due to discoveries in physics or chemistry.

Examples of improved technology for improved EE:

1. Lighting: The light bulb is a typical example of a technology that has radically evolved over the last few decades. Incandescent light bulbs produce light through heating a filament (3-5% efficient), fluorescent lights produce light by a complex ionization and spectral conversion process (30-50% efficient) and the most modern LED lights emit visible light through semiconductor physics (80-90% efficient).

2. Motors: Synchronous reluctance motors use complex control systems to manage the magnetic reluctance in order to create torque in a motor that is completely free of magnets. The technology is significantly more effective than using magnets and coils to create torque in the rotor. Not only are the motors smaller, but the construction requires less energy byproducts such as magnets.

3. Heat pumps achieve thermal energy transfer by controlling volatile evaporating and condensing of refrigerants. Heat pumps use electric power

## 3.4. UTILIZING INTRINSIC (UNAVOIDABLE) LOSSES

Total system efficiency can be improved by utilizing unavoidable losses through economic recovery methods.

Examples of utilizing intrinsic losses:

1. Combined heat power (CHP) plant: Heat is ‘cogenerated’ with electricity in such a way that it can be used effectively instead of lost to the environment.

2. Waste heat recovery from internal combustion engine radiators can be used for heating.

3. Thermo-electric generators on internal combustion exhaust gases create usable electricity.

4. Regenerative braking coverts the energy lost during braking into useable electrical or potential energy.

## 3.5. MANAGEMENT OF DATA

Energy consumption data from energy audits, smart metering systems and sensory actuators enable significant improvements to the efficiency of a system:

1. On an operator level: measured data can be used to identify and address ‘culprit devices’ that are consuming unnecessary energy.

2. On an automated level: Since human operators lack holistic understanding of complex energy systems, rule-based control and automatisation allows energy to used more efficiently. Building management systems and load balancing systems can be implemented to intelligently control energy consumption inside buildings. This mitigates avoidable losses that are incurred by the neglect of a building’s occupants.

## 3.6. BEHAVIOUR

The behaviour of the energy end-user a massively important consideration in the energy supply chain.  As explained in section 3.2, energy saved on the end-user side means that less energy has to be produced upstream. Individuals can implement simple actions with great effect. Examples of behavioural impacts on EE systems:

1. If an energy efficient cookstove is loaded with excess fuel due to user miscalculation, the fuel will be partially combusted and therefore wasted.

2. It is common practice for building occupants to leave lights on in unoccupied spaces. Even if building are retrofitted with the most efficient LED lights, some energy is still needlessly consumed due to human operation.

3. Significant improvements in the aerodynamics of heavy vehicles are meaningless if the drivers of the vehicles are not sensitised to use the vehicle in an energy efficient manner.

4. If a building management system is installed to optimise energy use, but the human operator does not calibrate effective setpoints, the system will not achieve the desired efficiency results.

5. The tire pressure on a vehicle directly impacts the rolling resistance. By correcting tire pressure, vehicle operators can increase fuel efficiency.

# 4. AREAS FOR ENERGY EFFICIENCY

Energy cannot be created or destroyed, but only moved from one form to another. This means that the end use of energy is contingent on a supply chain whereby a primary energy form is converted into a useable form. The illustrations below indicate different energy conversions for simple energy supply chains:

Intrinsic losses in the energy supply chain result in undesired forms of energy. For example, the function of a transmission line is to transmit electrical energy, but due to the resistance of the line, some of the energy is converted into heat, which is an undesired and wasted form of energy at that point in the system.

Efficiency can be improved by minimizing losses at every transition or transfer along the energy supply chain (represented by arrows in the figure above). Energy efficiency in the four major areas of the energy supply chain energy is discussed below.

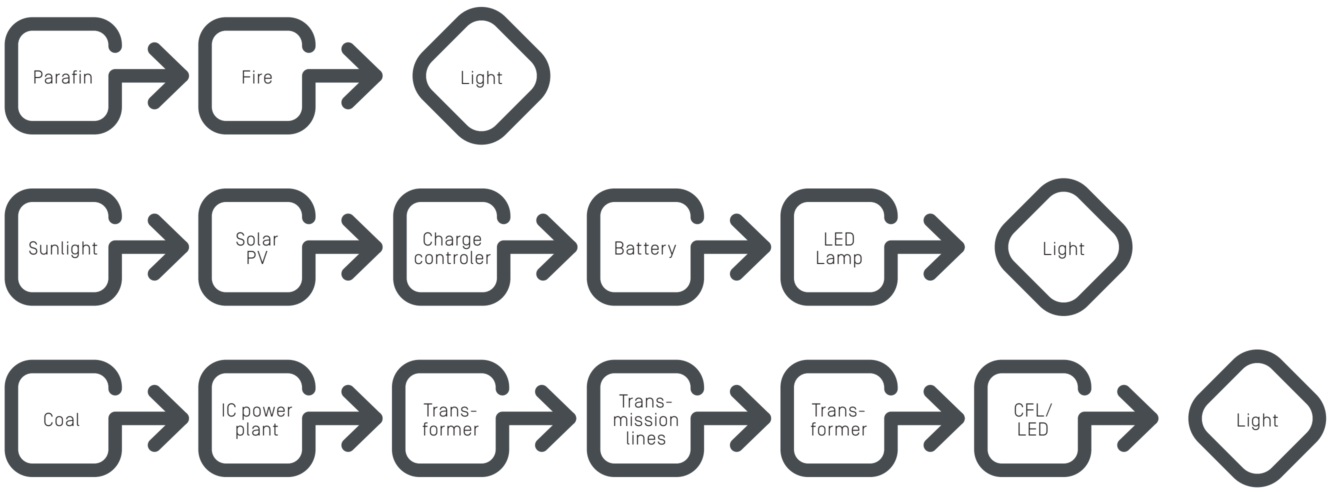



Table 3: Energy supply chains for three processes that result in the same energy outcome

## 4.1. GENERATION

Power generation converts a primary energy source into a useable form of energy. Figure 4 shows the generating efficiencies of the globe between 2011-2013. The world average for power generation is 40%, with about a third of the world's countries boasting power generation efficiencies of more than 50%.[10]

In countries such as Brazil, Norway, Iceland and Canada, the large amount of hydro-electric power generation leads to national efficiencies exceeding 60%. The apparent efficiency of electricity generation in several sub-Saharan African nations is attributed to the use of hydro-electric power and very low electrification rates. South Africa, the only sub-Saharan Africa that is more than 60% electrified, shows poor electricity generation efficiencies due to the nation's ubiquitous use of coal-fired power plants.

Power generation limits the availability of useable energy within an energy system. Downstream efficiencies allow the available resource to be used more effectively.

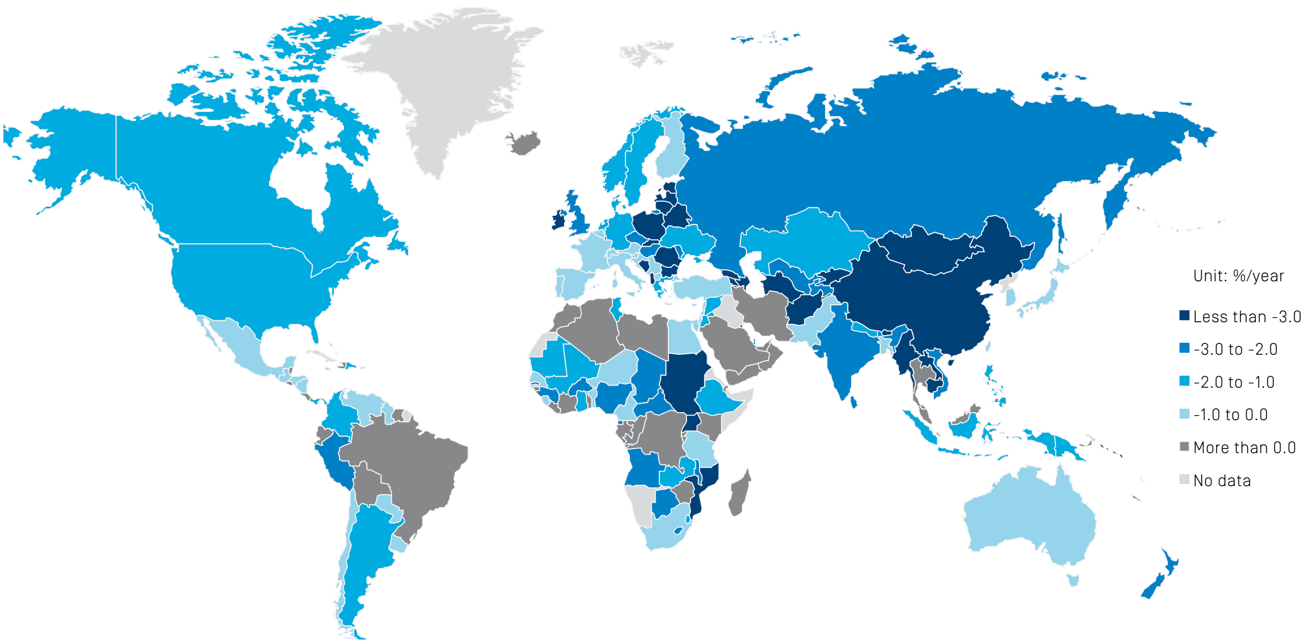



Table4: Energy efficiency of total electricity generation (2011)[11]

[10] aceee.org/topics/combined-heat-and-power-chp
[11] pg 5; The State of Global Energy Efficiency; Global and Sectoral Energy Efficiency Trends; ABB and Enerdata; enerdata.net

## 4.2. TRANSMISSION AND DISTRIBUTION

Transmission lines and electrical distribution systems are employed to transfer electricity from one location to another. Ohmic losses in transmission lines are improved by the following two methods:

1. Transferring energy at higher voltages by using step-up transformers.

2. Improving the materials that are used for conduction.

Fuel transport creates another important context for energy transfer and distribution. If biomass fuels are used to generate energy, the energy overheads for transporting the fuel should be taken into account, especially for biofuels with low calorific values.

## 4.3. STORAGE

Due to the intermittent nature of many renewable energy systems, energy storage forms an essential part of these systems. For energy storage mechanisms, the concept of energy efficiency refers to the full round-cycle of AC-AC or DC-DC conversion. In electrical batteries, for example, this will refer to the coulombic losses during battery charge compared to voltaic losses during battery discharge. For pumped storage, on the other hand, it will refer to the electrical energy into the pump during the pump phase compared to the electrical energy that is created during the generation phase.

## 4.4. CONSUMPTION

End-use consumption occurs when energy is converted into its final useful form. As explained in Section 3.2, a single percent increase in the efficiency of an end-use device can lead to significantly compounded upstream savings. This concept will be further discussed in Section 6.3 below.

One of the greatest benefits of energy efficiency on the end use side is demonstrated by the ubiquitous deployment of solar home systems within the EEP S&EA portfolio. These systems are only economically feasible due to the high conversion efficiencies of LED lamps. If less efficient incandescent lamps are used to generate the same intensity and duration of light, the solar PV and battery storage systems would be significantly larger, which would not be financially or practically viable.

In rare cases where power generation capacity exceeds consumption, it could be economically sensible to discourage energy efficiency. Although this is typically a short-term solution, it could be cheaper to consume energy inefficiently (whilst the number of consumers increases) instead of dumping excess energy at the production side. For example, if a hydro-electric plant powers an isolated microgrid with limited consumers, the energy produced by the grid must be dumped if it is not used by these consumers. This rationale will change as more consumers are connected to the grid. However, excessive consumption to compensate for over-sized production should not be encouraged since it could lead to long-term inefficient consumption habits; rather, effective sizing of power plants should be encouraged.

# 5. ECONOMICS OF ENERGY EFFICIENCY

## 5.1. ECONOMIC BENEFITS

When designed properly from the start, energy systems can be optimized to create both immediate financial savings and lifetime environmental benefits.[12] Energy efficiency is a concept which permeates through the entire energy supply chain and affects all parts of energy creation, transfer and use. It is a low-risk investment, where proper implementation guarantees returns.

Energy efficiency can allow weaker economies to leapfrog over ineffective power usage and directly implement advanced technologies that are cost effective to operate. In the long-term, EE makes it cheaper to save fossil fuels than to buy these fuels. This was seen in Kenya when the utility started clamping down on utility losses (in addition to increasing recovery of outstanding fees from nonpayment and other administrative efficiencies). This can be seen in figure below from a study done by the world bank.

With the right technologies and application, EE can be exercised profitably. An important concept in the realization of energy EE projects, is that of tunneling through the cost barrier, whereby non-direct energy saving benefits are considered as part of the cost analysis.

## 5.2. COST BARRIER TUNNELING

A typical example of tunneling through a cost barrier can be explained from the building sector. Most buildings require a heating or cooling system to maintain comfortable living conditions in the structure. At point **(a)** on the graph below, the investment cost of heating or cooling systems is already considered. As the capital expenditure is increased on thermal insulation in the structure, there comes a point **(b)** where the energy losses that are mitigated by the increased insulation are so insignificant that a large heating or cooling system is no longer required.

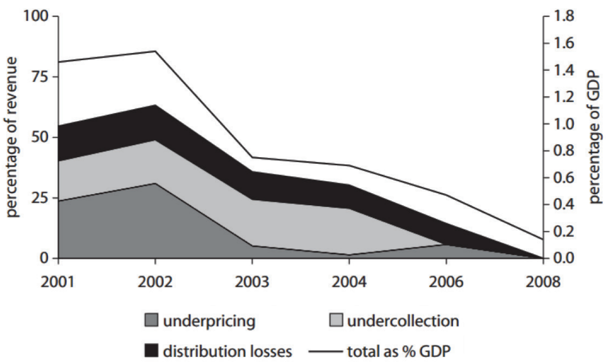



Figure 5: The black band indicates the distribution losses that were reduced by clamping down inefficiencies in the system and brought down to the minimum in 2008.[13]

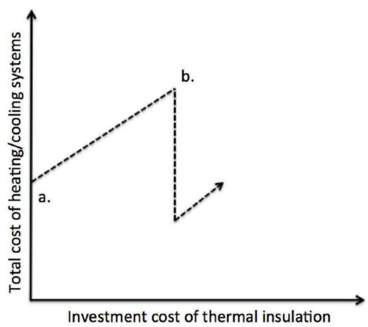



Figure 6: Hypothetical illustration of cost-barrier tunneling in a building with poor insulation. This concept illustrates that the investments required for saving large amounts of energy can actually be smaller than the investment for saving smaller amounts of energy.

[12] Natural Capitalism, A Lovins, 1999, NC-99-06
[13] pg 170; Africa's power infrastructure; Directions in Development; A. Eberhard, O. Rosnes, M. Shkaratan, H.Vennemo; 2011 The International Bank for Reconstruction and Development; The World Bank

Although proper insulation is expensive, structures that adhere to aggressive insulating standards (such as Passivhaus) provide ample evidence that the investment in insulation often removes the need for air-conditioning and heating, or significantly reduces the size and operating costs of these devices.

The ideal situation would be to achieve reductions in energy use that are economically efficient where the benefits exceed the costs, so that both the upfront costs and the operational costs are lower.

## 5.3. COMPOUNDED EFFECTS OF DOWNSTREAM SAVINGS

Optimising the efficiency of one part of a system may lead to savings throughout the system, as these examples illustrate:

1. A vehicle's rolling resistance is directly proportional to the weight of the vehicle. By using advancements in material science to make a vehicle lighter, the rolling resistance is diminished. Consequently, every unit of energy saved at the wheels will save an additional 7units of energy that do not have to be wasted by engine and drivetrain inefficiencies. Consequently, a smaller engine is required to propel the vehicle, which leads to further weight savings, and consequently, to a further recalculation of engine size.

2. A liquid's flow is retarded by the diameter of pipes, as well as by sharp bends in the pipes. By increasing the diameter of pipes, flow is sufficiently improved that pumps can be made smaller. This results in less energy being used to pump liquid through the system. Although an increase in the diameter of a pipe has cost implications, the downsizing of the pump leads to lower capital expenditure and operational costs.

## 5.4. MARKET BARRIERS

There are several reasons for the market to reject EE technologies despite seemingly clear economic rationale for its adoption. Even if an EE technology seems to be cost effective in the long term, behavioural issues that preclude its adoption might be overlooked. These reasons are often complex cultural and sociological trends. This section will succinctly explore several issues with the adoption of EE technology.

### 5.4.1. CONSUMPTION AWARENESS

Many DC chargers for mobile phones and laptops are not optimized to switch off once the device is unplugged. These 'dumb' AC-DC converters constantly waste power, even when the devices they are designed for are not being powered. Similarly, consumer electronics are designed to have a 'standby mode' which allows for quick startup and stores system settings. This means that many modern electronic systems (such as computers, printers, kitchen appliances and home entertainment systems) still use power even when 'switched off'. In both cases, the retailer or principal agent hands over unnecessary operational expenses to the user since the low power mode or low cost chargers are not engineered for minimal power consumption. These devices influence the efficient end-use of energy within buildings.

These two examples bear relatively low salience in the general population, which means that interventions are necessary to create awareness of unintended electricity consumption. Clear labeling on all types of equipment is also necessary to create awareness for end users.

The Australian Government's efforts to implement effective information interventions are exemplary: clearly visible labeling and easily understood star ratings on different household appliances notify users of the efficiency rating.[14]

[14] energyrating.gov.au/about/what-we-do/labelling

### 5.4.2.
### UN-PRICED COSTS AND HIDDEN BENEFITS OF ENERGY EFFICIENCY

The investments rationale for EE should not only consider CAPEX and OPEX, but ought to be more holistic in terms of the benefits. The dialogue with regards to pushing EE should be structured around the holistic benefits that compliment operational savings. Examples of this argument are succinctly listed below:

- EE buildings can boost sales in retail stores. Wallmart has increased sales figures by retrofitting their stores with natural lighting.15

- EE buildings can increase productivity of human occupants - since worker costs can be up to 3 orders of magnitude more than energy costs, the improvement in labour efficiency is a massive saving which is typically not factored into the cost calculations for EE investments. EE improvements at companies like Lockheed, Verifone and Boeing demonstrate this concept.16

- The unpriced cost of damage to the environment is currently not covered by energy end-users in the public, but is transferred to future generations or to companies and governments that pay carbon taxes. Since end-users carry very little liability for poor energy consumption (beyond operational costs), there is also a poor public understanding of the damage caused to the environment. The un-priced cost of irresponsible energy consumption is an issue which requires active intervention from world governments to raise the level of awareness amongst all end-users and to make the responsible use of energy a civic matter.

[15] ciralight.com/blog/what-business-benefits-does-natural-lighting-bring
[16] A Literature Review of the Effects of Natural Light on Building Occupants; L. Edwards; National Renewable Energy Laboratory; 2002

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