ASCENDIS

Advisory Services on Climate, Energy and Development Issues

Overview of costs of sustainable energy technologies

Energy production: on-grid, mini-grid and off-grid power generation and supply and heat applications

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LIST OF ABBREVIATIONS

ARE	Alliance for Rural Electrification
BOS	balance of system
CHP	combined heat and power
CSH	concentrating solar power
CSP	concentrating solar heat
CAPEX	capital expenditures
EIA	US Energy Information Administration
EJ	exajoule
ESMAP	Energy Sector Management Assistance Programme (World Bank)
EUR	euro
GW	gigawatt
GWh	gigawatt-hour
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel for Climate Change
IRENA	International Renewable Energy Agency
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelised cost of energy
MSW	municipal solid waste
MVA	megavolt-ampere
MW	megawatt
MWh	megawatt-hour
O&M	operation and maintenance
OPEX	operational expenditures
PV	photovoltaic
R&D	research and development
RE	renewable energy
RET	renewable energy technology
REN21	Renewable Energy Policy Network for the 21^{st} Century
SHS	solar home system
STS	solar thermal system
TWh	terawatt-hour
UN	United Nations
TAF SE4All	European Union Technical Assistance Facility for Sustainable Energy for All
UN	United Nations
USA	United States of America
USD	US dollar
yr	year
W_p	peak-Watt
W_{th}	thermal Watt
WEC	World Energy Council
WEO	World Energy Outlook
WWEA	World Wind Energy Association

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1. INTRODUCTION

1.1 Background

There are many possible technologies available for energy generation, based on fossil fuels, or using regenerable energy (biomass) or renewable sources of energy (solar, wind, hydro, etc.). Nonetheless, it is often asked 'what is the price/cost of this technology' as means of selecting one technology over the other, and the above-given description already indicates there are often too many differences and characteristics to give an easy answer. Often policy-makers and decision-makers make requests for information on energy technology costs to be put in background papers, presentations, project proposals and for activity programming. The purpose of this report is to provide an overview of the different investment cost and annual cost of operation and maintenance of sustainable energy technologies.

At first look, comparing energy production and end use technologies seems straightforward; you can obtain a technology at a certain price. However, technologies differ in the way power is generated and the scale the technology can be used. They differ in energy resource variability and availability, specific local and natural conditions, patterns of use of the energy produced and technology maturity. There are big differences in cost of the technology and fuels and costs of operation and maintenance, and that are not static but fluctuate or change over time. Even for one technology, costs can differ per subtype or per model, depending on its application and in which country it will be bought and used.

1.2 Methodological issues in cost comparisons

Thus, in practice making such comparisons is quite complicated:

- Data provided may reflect the writer's bias towards a technology, e.g. by reporting the lower cost range of a preferred technology against the higher cost range of the disfavoured technology
- Data found in literature can diverge widely; the author of this report had once to report on costs of small hydropower to find out that these ranged in various reports (from UN, World Bank, etc.) ranged from USD 1500 to 7000 per kW installed capacity. These differences can be explained by:
    - o Economic of scale, i.e. cost generally decrease (slightly) per installed capacity);
    - o Large fluctuations in energy resource availability and/or
    - o Large power demand peaks and low load utilization in off-peak hours;
    - o Non-equipment cost. The lower range often gives the bare technology cost, while towards the upper range, project organisation and preparation cost are included. Costs do not include equipment only. For example, installing a hydropower station for rural electrification has the cost of organising, planning and designing the station, getting authorities' approvals and permits, engaging the local community, which requires the (expensive) support of consultants or companies. If covered by development assistance, these costs are often absorbed by the assistance project and may not be fully not reported;
- Many renewable energy technologies have high investment cost, but relatively low operating cost, while many fossil fuel alternatives have low initial investment but high annual cost (basically fuel cost and overhaul expenses). One methodology is to compare lifecycle cost; you divide the initial investment over the technologies' lifetime and use a certain discount rate to arrive at the levelised cost of energy (LCOE, see Box 1). However, it can be questionable what the actual lifetime is and what discount rate

needs to be used. Also, a system may consist of technologies with different lifetimes. In a solar PV system with battery backup the panels should last 20 years, while the battery may go flat after 5-7 years. Cost of batteries can be quite substantial; in other words, the cost of battery replacement should be factored in;

- Levelised cost reported are not always compatible due to difference in resource availability. For example, one can image that the LCOE of solar installation in Atacama desert in Chile will be different from the Tierra del Fuego one.
- Capital expenditure (CAPEX) cost break down in three components: 1) development and preparation, 2) equipment, 3) balance of plant or system. Balance of system or plants include cost components such as civil works, construction, wiring, etc., each with their own useful or technical lifetime;
- Another crucial factor is the actual energy consumption in comparison with the potential energy generation capacity, expressed by the load utilization factor (see Box 1). This works in two ways, looking at a) supply and b) demand:
    - On the supply side, some renewable technologies can be quite variable, notably solar, wind, run-of-the-river hydro and biomass, depending on how the wind blows, the sun shines and the harvest of biomass was successful. Variability is on a daily, monthly, seasonal scale which needs in-depth investigation with time-series energy resource analysis which has a cost and is not always clearly mentioned;
    - On the demand side, there is wide difference between grid-connected and off-grid technologies. To illustrate the difference, the example of hydropower. If the river flows and all the power generated can be fed into the grid, the load utilization factor can be impressive; however, in case of small grids the load utilization factor is often not more than 30%; the installation's capacity may be designed to meet the evening hours peak in the town (when households switch on their lights), but much of the capacity will be idle for the rest of the day; the economics can be improved when the peak is shaved, by combining with efficiency measures while stimulating other (productive) uses during day time
- Technologies can be difficult to compare when taxes are taken into account. Some countries tax technologies in a hefty way; import tax 15-20%; sales tax 20%, etc. Other authorities give tax benefits or other incentives that can be of the same order of magnitude. Costs per country can also differ as costs of inputs (labour cost, fuel cost, interest rates) can differ widely. Comparing one figure from one report from one country with another often is difficult, unless such (dis)incentive cost details are known;
- Costs are often given for a specific year. This gives three problems, a) the exchange of a currency can be fluctuating and if converted at a non-average rate can give biased results in terms of costs; b) there is inflation, so when comparing 2010 figures with a 2015 report inflation factors should be factored in (normally the average of the IMF-reported consumer's price index is a guideline); c) costs of technology and their operation may have changed. Sometimes in reports lifetime of fossil fuel generation costs are reported using a fuel price which happened to be at the peak; only to find out that next cycle it was only half of the reported price, making the cost analysis very questionable; d) cost of some renewable energy technologies (in particular solar PV) have a tendency of rapid decrease over time (so that the latest data should be used where possible).
- By varying slightly with discount rate, financing cost, depreciation, tax assumptions, and CAPEX and OPEX estimates in Excel spreadsheet analysis, it is often not too difficult to describe any technology more favourably by changing the initial parameters, while drawing a more expensive picture of the technology your report-funding agency may not favour. Related to this, incentive regimes have often spurred technologies by lowering the O&M cost and/or CAPEX cost, but also in this way discouraging the longer-term innovative development with lower costs of technology.

In conclusion, giving one sole figure, cost per kW or cost per kWh, to characterize the price of an energy production or end-use technology can be deceptive. Despite the above-mentioned limitations, some reputed organization have delivered quite some credible assessments and provide summary of costs that are basically the basis of the assessments in this reports, such as IRENA, World Bank, World Energy Council, REN21, and UN organizations (UNDP, UNIDO, UNEP).

Box 1 Cost metrics

Cost of energy technologies include equipment, organization and installation, operating and maintenance. Financing expenditures are part of the costs. However, in comparing technologies financial costs should in principle be left out of the initial cost assessment. The idea is that costs of technologies are compared on their merit (benefits vs costs). Often the financial sector may have a bias towards new or innovative technologies as opposed to the proven ones. If projects or technologies need funding, criteria are often applied that disfavour these technologies.

Four cost metrics are frequently referred to in this report:

- *Investment cost* or *capital expenditure* (CAPEX), which includes the total cost of project development, installation and construction, including equipment cost;
- *Operating expenditures (OPEX*), are the annual (variable and fixed) expenditures for operation, administration, maintenance and, if applicable, fuel cost
- *Capacity factor* or load (utilization) factor is the ratio of the net energy production in a given year that could have been generated at full-capacity operation (i.e. at 8,760 hours). Capacity is not full used due to non-availability (scheduled maintenance and overhaul work), resource limitations (variability and unavailability at certain time per day or seasonally) and low demand (when capacity is idle);
- *Levelised cost of energy* (or electricity) – LCOE: the value of lifecycle costs (e.g. in USD/MWh) of producing a unit of energy (MWh) of a specific technology. One can also say the LCOE is the price that must be received per unit of output to reach a financial return (break-even) over its lifetime

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t : investment expenditures in the year *t*

M_t : operations and maintenance expenditures in the year *t*

F_t : fuel expenditures in the year *t*

E_t : electrical energy generated in the year *t*

r : discount rate (often taken as 10%)

n : expected lifetime of system or power station

Notes:

- Some caution must be taken when using formulas for the levelised cost, as they often embody unseen assumptions, neglect effects like taxes, and may be specified in real or nominal levelised cost.
- Other versions of the above formula do not discount the electricity (or energy) stream

1.3 World energy production and consumption

As of 2014, renewable energy provided an estimated 19.2% of global final energy consumption. Of this total share, traditional biomass, used primarily for cooking and heating in remote and rural areas of developing countries, accounted for about 8.9%, and modern renewables (not including traditional biomass) increased their share slightly over 2013 to approximately 10.3% (REN21, 2016).

Figure 1 Estimated RE share in global final energy consumption in 2014

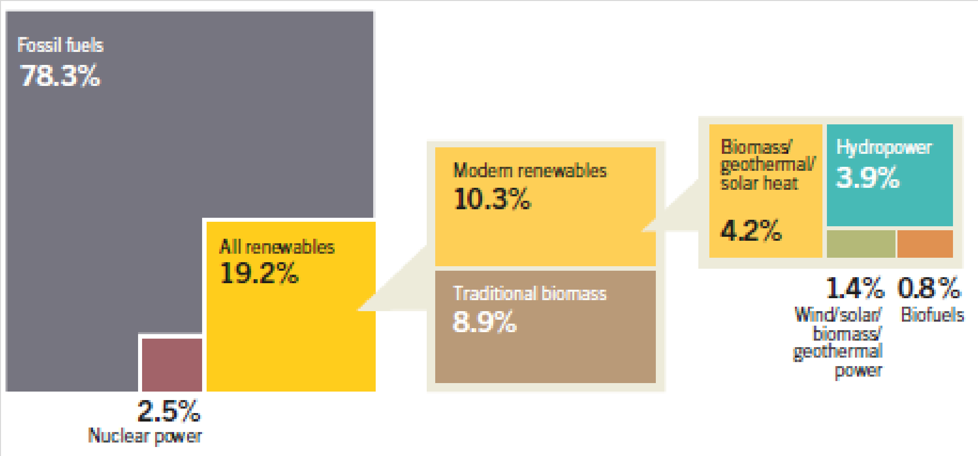


Figure 2 Estimated RE share in global electricity production in 2015

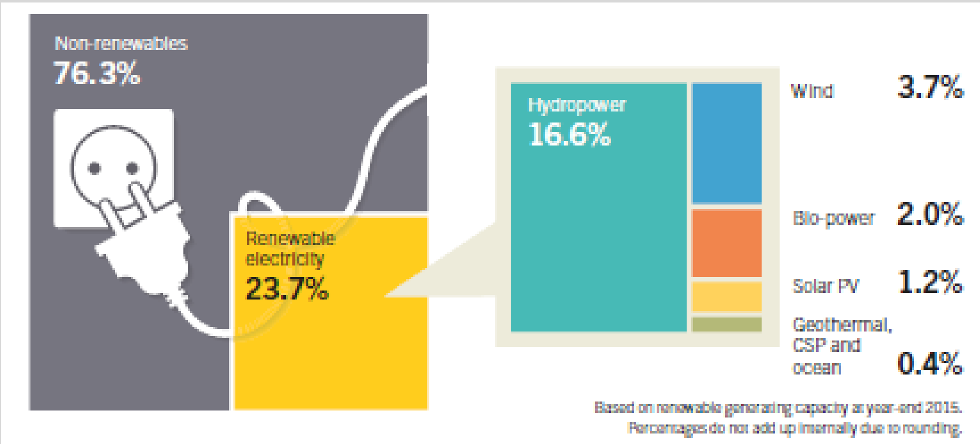
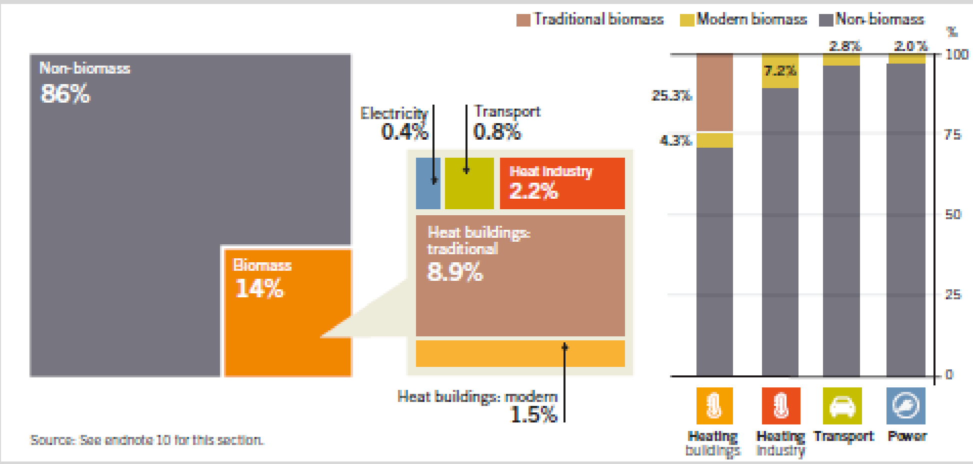


Figure 3 Share of biomass in total final energy consumption (2014)



Source: REN21 (2016)

Figure 4 World electricity access and lack of access (2013)

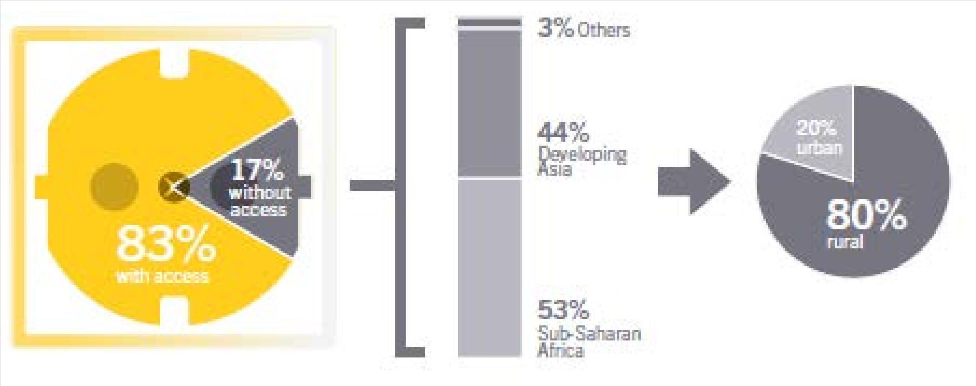
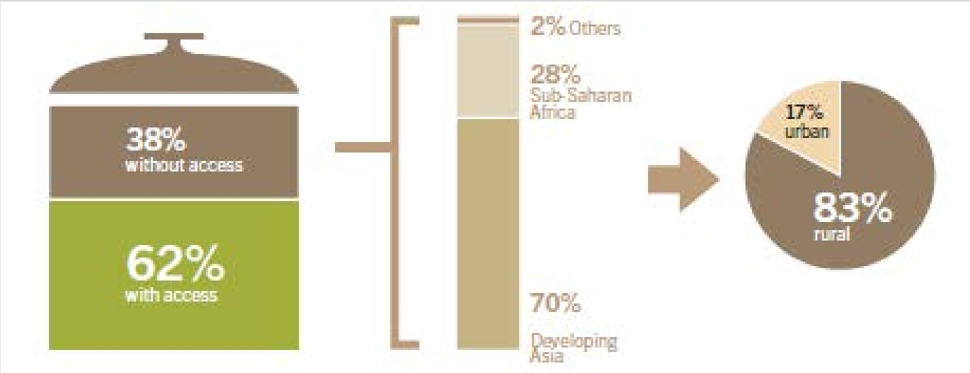
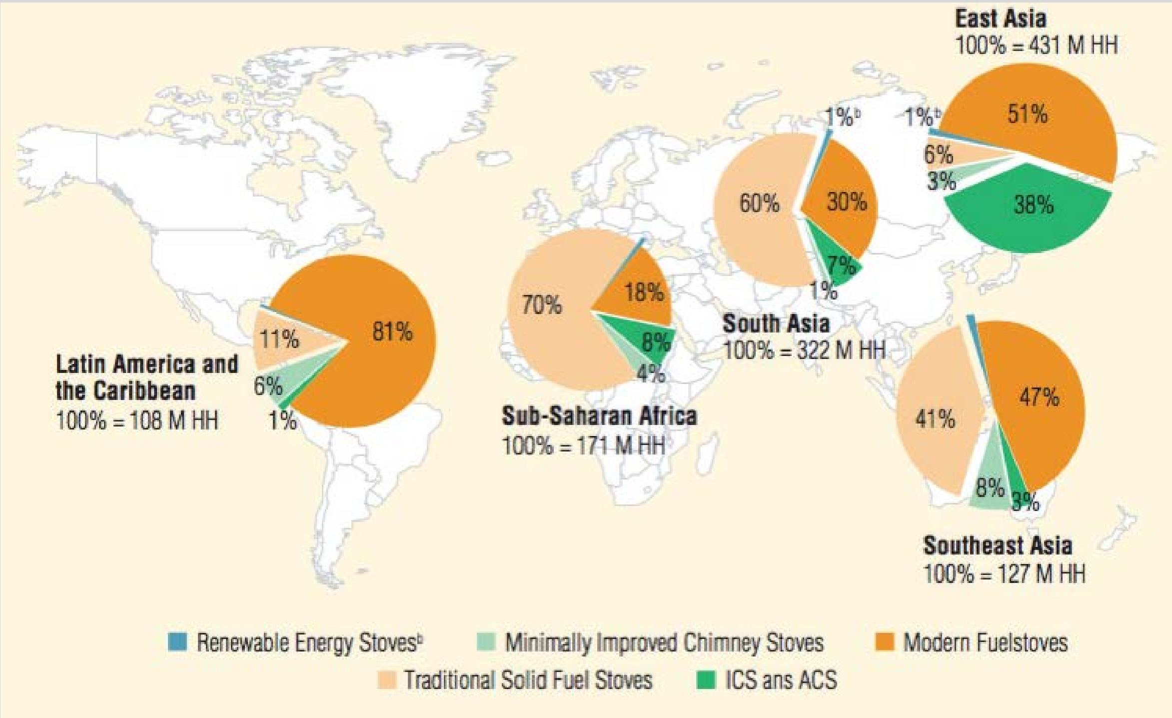


Figure 5 World clean cooking access and lack of access (2013)



Source: REN21 (2016)

Figure 6 Biomass cooking technology use per region



Source: WBA (2016)

2. ELECTRICITY GENERATION

2.1 Hydropower

Hydropower accounts for one-fifth of today's power supply, but less than 10% of the estimated technical potential has been utilised (WEO, 2014). Hydropower, excluding pumped storage, is currently the largest renewable power generation source, with a global installed capacity of 1,064 GW in 2015 (REN21, 2016), generating about 3,940 TWh. There is a big difference in cost between small and large scale hydro. But the investment costs differ also due to the type of the plant, if they are run-of-river plants or if reservoirs are required. There is no good definition of what is large, medium and small-sized, which may differ per country. IRENA (2012) mentions: large hydro: > 100 MW (feeding into grid), medium hydro: 20-100 MW (almost always fed into a grid), small hydro: (1-20 MW, usually grid-connected), mini-hydro: 100 kW-1 MW (stand-alone, mini-grid or grid-connected), micro hydro: 5-100 kW (usually stand alone or small-grid in remote area) and pico-hydro (below 5 kW)

Table 1 Estimates of investment and levelised cost of hydropower

2010	Installed cost (USD/kW)	O&M cost (%, installed cost)	Capacity factor (%)	LCOE (2010 USD/kWh)
Large hydro	1050-7650	2-2.5	25-90	0.02-0.19
Small hydro	1300-8000	1-4	20-95	0.02-0.27
Refurbish/upgrade	500-1000	1-6		

Taken from IRENA RETs (2012): Cost Analysis Series Vol.1 3/5: Hydropower. Levelised cost assume 10% cost of capital and lifetimes of 40 years. Mini and small hydro

	Installed cost (USD/kW)	O&M cost (USD/MWh/yr)	Capacity factor (%)	LCOE (USD/kWh)
Large hydro	1590-4150	20,000-62,000	20-75%	0.024-0.302
Small hydro	1400-3680	15,000-85,000	23-80%	0.019-0.314

Source: WEC (2013)

2013-14	Installed cost (USD/kW)	O&M cost (%, installed cost)	Capacity factor (%)	LCOE (USD/kWh)
Medium-large	1050-7650			0.02-0.20
Small hydro	1000-4000	1-4%		0.02-0.10
Mini (< 1 MW)	3400-10000			0.27

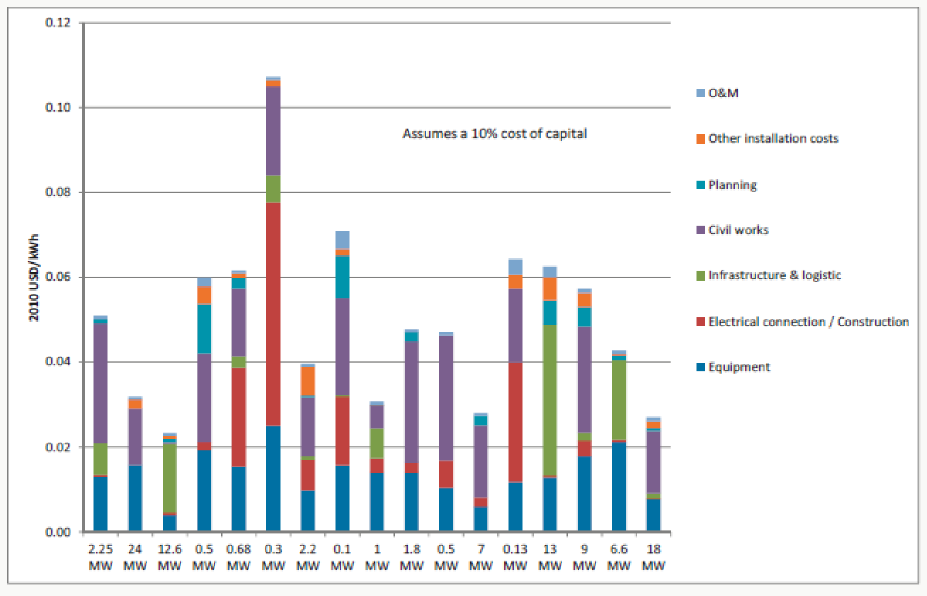
Source; adapted from IRENA (2015)

2013-14	Installed cost (EUR/kW)
Large (> 100 MW)	1000-2000
Small (~ 10 MW)	1800-3000
Mini (~ 1 MW)	2500-4000
Micro (~ 50 kW)	3500-5500

Source: EU TAF for SE4All

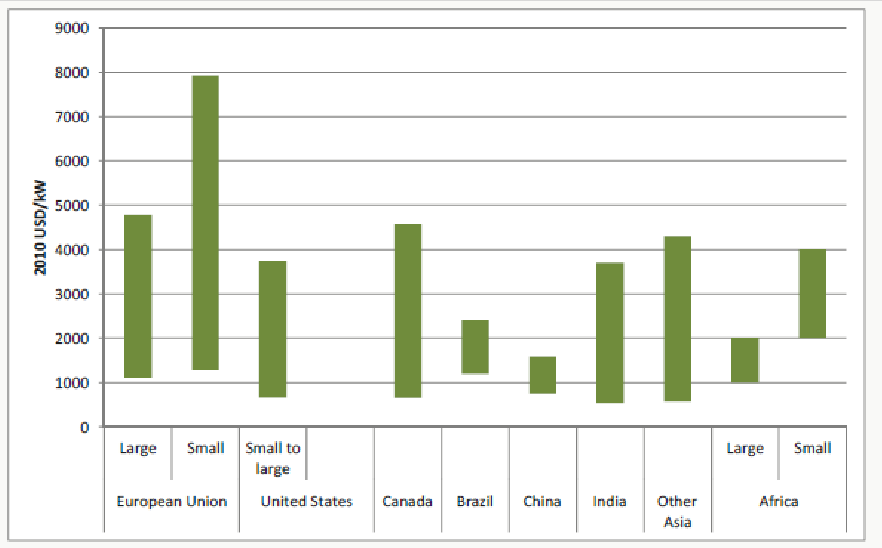
Hydropower plants can be connected to the national or main grid system. Hydropower plants not connected to the national grids are classified as mini-grid (or micro-grid) systems. Cost estimates reported can differ widely, based on capacity factors (there is huge variation from 30 to 85%, and difference between grid-connected and mini-grid systems), cost included in the estimate (e.g. only technology cost or also project and community organization costs), cost of components in a country (cement, steel). There has been little systematic collection and cost of hydro tend to be very site-specific; investment costs quoted in studies can range from USD 1,000 to 7,500 per kW (IRENA 2012, Fig.4.1). IRENA (2015) gives USD 450-3,500/MW as typical cost with LCOE varying between USD 0.02-0.15/kWh (2014 figures).

Figure 7 The LCOE of small hydro for a range of projects in developing countries



IRENA (2012), page 30

Figure 8 Total installed cost per region/country



IRENA (2012), Issue 3/5,page 18

A typical hydro generating station can be described under two main headings: civil works and electro/mechanical equipment. The largest share of installed costs for large hydropower plant is typically taken up by civil works for the construction of the hydropower plant (such us dam, tunnels, canal and construction of powerhouse, etc.). The electro-mechanical equipment costs tend to be higher in small-scale projects, contributing from 18% to as much as 50% of total cost. For projects in remote or difficult to access locations, infrastructure costs can dominate total costs (IRENA, 2012). The design of hydropower schemes is highly complex and time consuming. It requires extensive investigations and surveys in many technical domains including geology, seismology, topography, hydrology, geotechnical, construction material engineering, electro-mechanical and electrical engineering and much more. The implementation (up to commissioning of operations) of a hydropower scheme project depends of course on its dimension; for a totally new project, the duration from identification to commissioning can span from 5 years to more than 12 years (TAF SE4All, 2015/16).

Due to the maturity and relative simplicity of the technology the economics can be very attractive if the right location can be found. Hydropower levelised cost of energy (LCOEs) are usually cost-competitive without financial support, especially for adequately sited large hydro. Average LCOE in OECD countries is about USD 0.09-0.10/kWh for large hydro and USD 0.10-0.15 for small hydro, while in many developing countries (where the economic potential has not been fully exploited) the LCOE ranges USD 0.02-0.11/kWh (IRENA, 2015). Small hydropower projects have an average LCOE of 0.05/kWh and can be a very attractive electrification option, providing low-cost electricity to remote communities or for the grid. However, the main barrier to development is the very high capital cost of building the installation. Other barriers to investment include low seasonal river flows and elevated levels of water use (WEC, 2014). Hydropower is a mature technology, with limited cost reduction potential in most settings. However, significant low-cost potential remains to be exploited in many countries outside the countries of the OECD.

2.2 Solar photovoltaics

Table 2 Estimates of investment and levelised cost of solar PV

	Installed PV system cost (USD/kW)			Levelised cost of energy USD/kWh)		
Installed PV system cost	Utility scale	Residential (w/o battery)	Residential (w/ battery)	Utility scale	Residential (w/o battery)	Residential (w/ battery)
2010/11	2640-5000	3070-5800	4000-6000	0.20-0.59	0.25.0.70	0.36-0.71
2014/15	1300-5400	1860-5100	3800-4300	0.08-0.42	0.14-0.47	0.31-0.52
2030	1060-1380	1500-1800				

Source large and small hydro: IRENA RETs (2012): Cost Analysis Series Vol.1 4/5: Solar Photovoltaics and IRENA (2015). LCOE assumes a 10% cost of capital. Efficiency (residential): 14% (2010/11, c-Si PV) and 8-12% (utility; amorphous/thin film) and 17% and 11-17% in 2015 respectively).

Components	Life (yrs)	Cost per kW installed (in USD)			
		Utility-scale	Roof-top residential	Small (w/o battery)	Small (w/ battery)
PV modules	20-25	660-850	660-850	730-850	730-850
Inverters	5-10	230-750	270-800	270-800	270-800
Wiring; electrical		240	240	240	240
Battery bank					1200-1500
Structure/mount		300	550	300	300
Installation, site preparation, etc.		650	130-220	150-200	200-600
Total cost		2000-2600	1900-2800	1600-2400	2900-4300
LCOE (USD/kWh)		0.10-0.30	0.14-0.46		

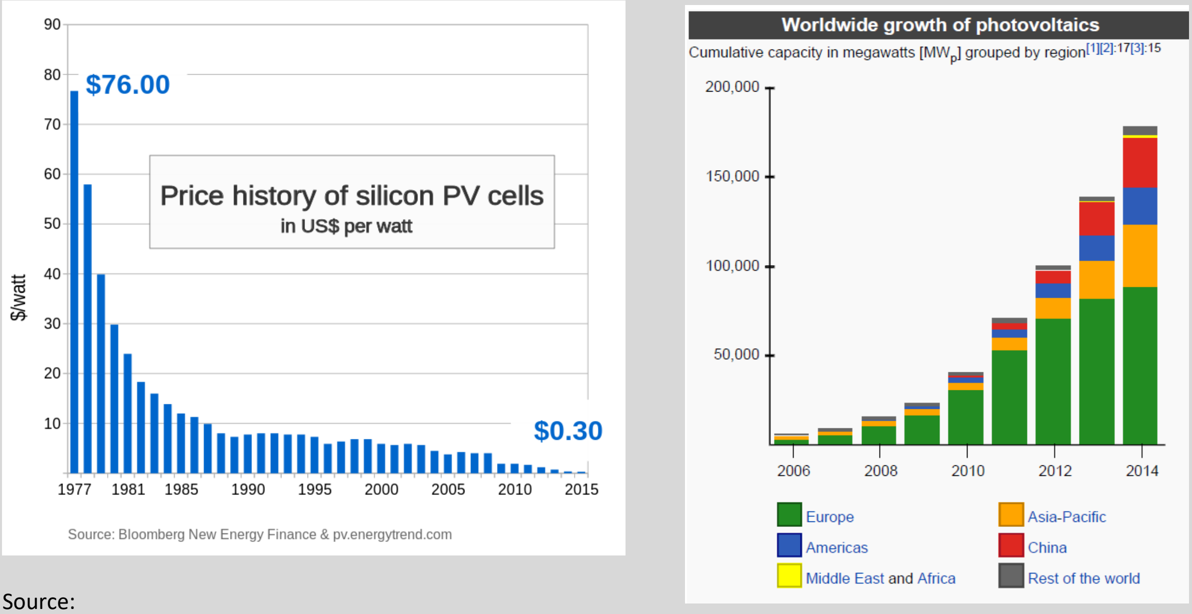
Own analysis, based on IRENA (2012), IRENA (2015), TAF SE4All (2015 and 2015/16). Assumed annual energy production is 800-2000 kWh per m2 per year, depending on latitude. In terms of size installed cost of PV range from USD 0.09-0.16 (> 100 MW), to USD 0.11-0.18 (10-100 MW), USD 0.13-0.20 (1-10 MW), USD 0.15-0.23 (10 kW-1 MW, ground) and USD 0.17-0.25 (1 kW-1 MW, roof)

PV plants	Installed cost (USD/kW)	O&M cost (USD/kW/yr)	Efficiency (%)	LCOE (2010 USD/kWh)
w/o tracking	1050-2660	11-60	11-20%	0.08-0.44
w/ tracking	2370-6210	40-126	16-29%	0.09-0.45

WEC (2013), based on data from China, India, Spain, USA, Australia, Germany and Japan. W/ tracking for W. Europe and USA only

Photovoltaic systems (PV) are made of PV modules. The smallest unit in a PV module is the solar cell, which convert the light into electricity. PV is one of the fastest growing renewable energy technologies and it is expected that it will play a significant role in the future global electricity generation mix. Large-scale

Figure 10 Trends in costs of solar PV and market penetration

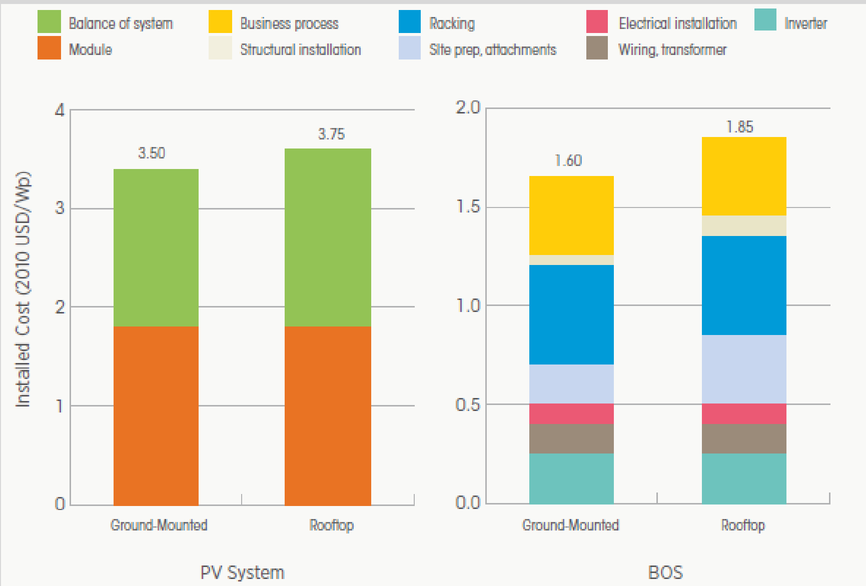


Source:
Global Market Outlook for Solar Power 2015-2019", http://www.solarpowereurope.org; Global Market Outlook for Photovoltaics 2014-2018"; http://www.epia.org., IEA, 2014; Technology Roadmap: Solar Photovoltaic Energy

grid PV technology can be used on a variety of scales. Utility PV plants (with a capacity of several MW) are designed for the supply of power into the electricity grid. Roof-top solar PV systems are often associated with buildings: either integrated into them, mounted on top of the roof or nearby on auxiliary structures (if the building itself cannot use all energy produced by PV, the owner need an agreement or PPA if he wants to sell excess energy to the grid). Solar home systems (battery operated solar system on a house, clinic or school) as well as pico-PV systems (e.g. solar lanterns) have experienced significant development in recent years for remote rural areas far from the grid. Solar water pumps can be competitive vs. diesel pumps when off-grid, depending on load, depth and water storage needs.

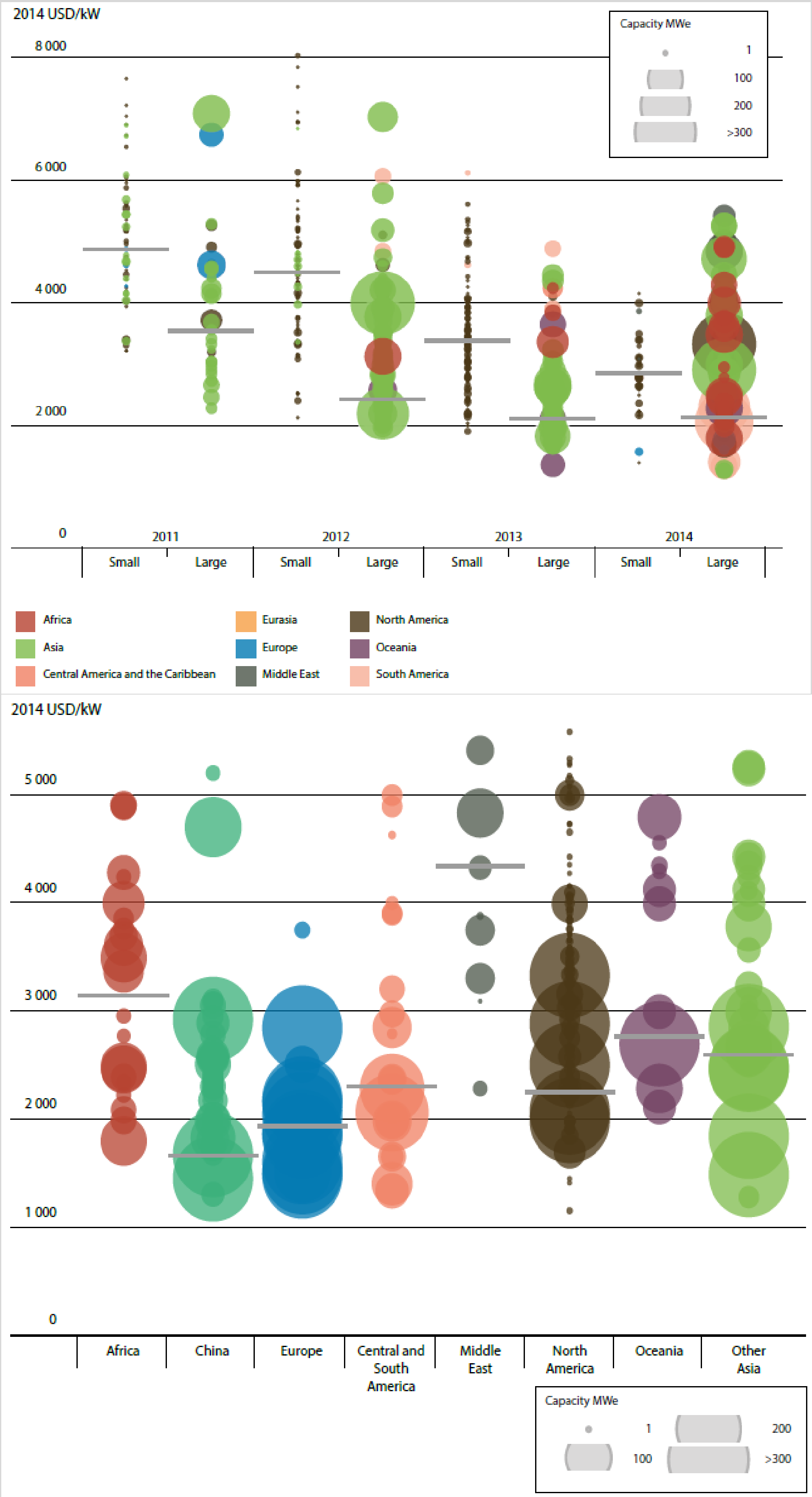
Large part in the cost of a PV system are the PV modules (about 30-50%), followed by balance of system cost (BOS, 20-70%) and in, stand-alone systems, the battery (usually lead-acid).

Figure 9 Cost breakdown of conventional PV system in USA (2010)



Source: IRENA (2012), Vol. 1 4/5, Fig. 4.5

Figure 11 Trends in costs of solar PV and market penetration



Source: IRENA (2015). Fig.5.13-14

The cost of PV modules has dropped significantly. Solar PV module prices in 2014 were around 75% lower than their levels at the end of 2009. Between 2010 and 2014 the total installed costs of utility-scale PV systems have fallen by 29% to 65%, depending on the region; the global average LCOE of utility-scale solar PV has fallen by half in four years, while the LCOE of residential systems in selected countries has fallen by between 42% and 64% since 2008 (IRENA, 2015). The most competitive utility-scale solar PV projects are now regularly delivering electricity for just USD 0.08 per kilowatt-hour (kWh) without financial support. With today's very low solar PV module prices, the greatest source of future cost reduction potential is in the balance of system costs, notably the soft costs, and through reduced finance costs. The solar PV market was an estimated 227 GW in 2015 (of which 50 GW added in 2015; REN21, 2016).

2.3 Wind power

Wind power technologies are differentiated based on the axis of the wind turbine – vertical or horizontal – and their location – onshore or offshore. For the utility-scale market, horizontal-axis turbines are used exclusively. Between 2000 and 2010 the global capacity of onshore and offshore wind increased at about 30% per year, reaching 200 GW installed in 2010 and 433 GW in 2015 (WEC, 2014; IRENA, 2015; WWEA, 2015; REN21, 2016), generating 800 TWh in 2014. China has the largest share of installed wind capacity, 29% at the end of 2013. It is followed by the United States (19%), Germany (11%), Spain (7%) and India (6%).

Largest cost component is the wind turbine, about 50-60% usually on average. Prices of wind turbine have dropped since the 1980s), but fluctuated over the past decade. For example, for turbines (> 1 MW) prices

Table 3 Estimates of investment and levelised cost of wind power

	Installed PV system cost (USD/kW)		Levelised cost of energy USD/kWh)	
.	On-shore	Off-shore	On-shore	Off-shore
2010/11 2014	1330-3060 1280-2290	3700-5600 2700-5070	0.06-0.13 0.06-0.12	0.10-0.32 0.10-0.21
2010/12	1080-2450	4290-6080	0.047-0.136 (cap.factor 15-45%)	0.147-0.367 (cap.factor 32-42%)

Source: IRENA (2015), above and WEC (2013), below

O&M cost is typically 1.5-3% of capital cost (CAPEX) and 25-30% of LCOE or about USD 0.02-0.03/kWh for on-shore and USD 0.037-0.054/kWh for off-shore. Data on O&M is often not consistently reported, making comparisons difficult. WEC (2013) gives OPEX range of USD 10.7-28.8/kW/yr (on-shore) and USD 100-160/kW/yr for off-shore.

Capital cost breakdown (2010/11 data)	On-shore	Off-shore
Wind turbines	64-84%	30-50%
Civil works and construction	4-16%	15-25%
Grid connection	9-14%	15-30%
Planning and development	4-10%	8-30%

IRENA (2015) and IRENA (2012), Vol. 5.5 Wind Power. Wind turbines: production, transportation and installation; Civil works: installation, foundation, site preparation and access road. Grid connection: cabling, substations and buildings. Planning and development: engineering, licensing, consultancy, permits

Wind turbine cost	Installed cost (EUR/kW)
Wind turbines (> 1 MW)	1500 (1060-2450)
Wind turbines (250 kW-1 MW)	2850 (2300-3400)
Medium (50 kW-500 kW0	3000 (2500-3500)
Small (1.5-50 kW)	5000 (3000-7000)

TAF SE4ll (2015).

increased from about USD 755/MW in 2000/02 to USD 1465 in 2007, peaking at around USD 1720/MW in 2009 and dropping to about USD 1400/MW in 2012 in USA; in China wind turbine prices were USD 1040/MW in 2007, dropping to about USD 630-680 in 2011-14. These trends reflect growing demand for turbines, fluctuating cost of commodities and increasing sophistication of wind turbine design. IRENA (2012) mentions in its table 5.3 that cost of installed onshore wind may drop over 10%-30% over 2011-2030.

Figure 12 Installed wind power capacity

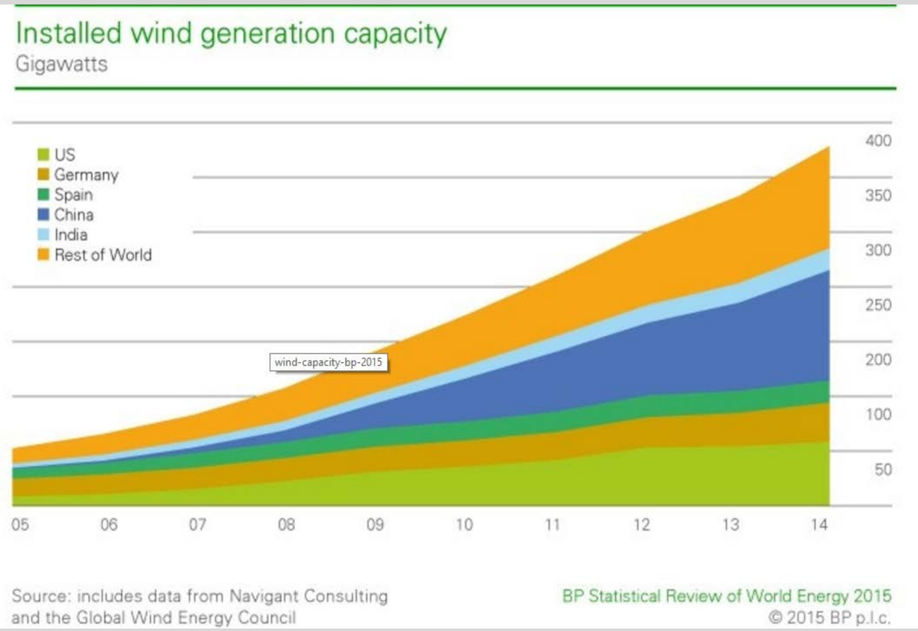
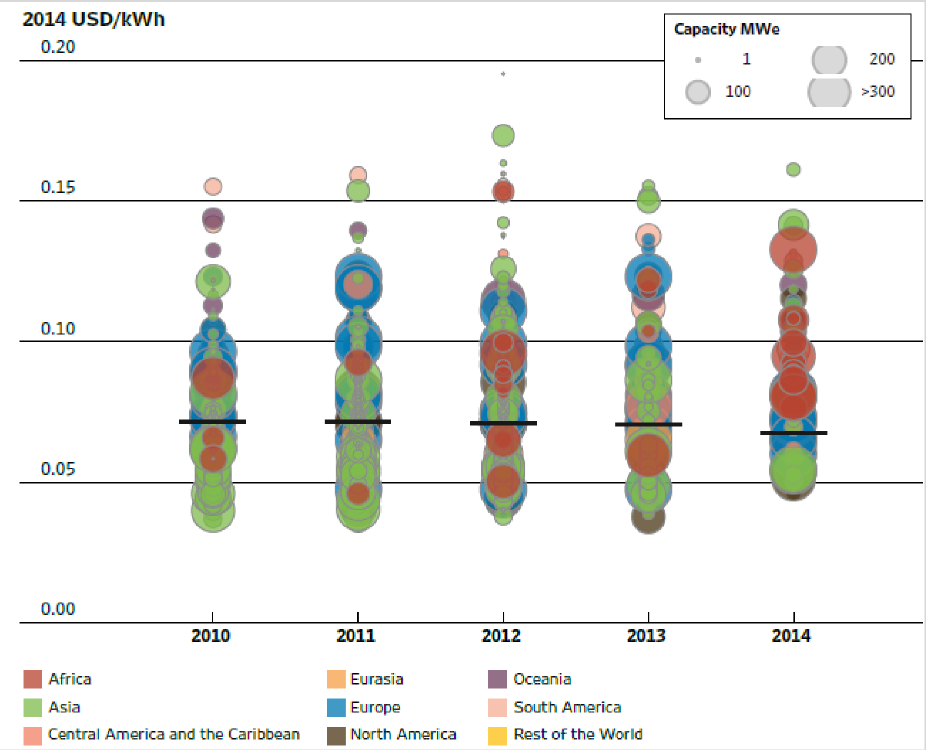
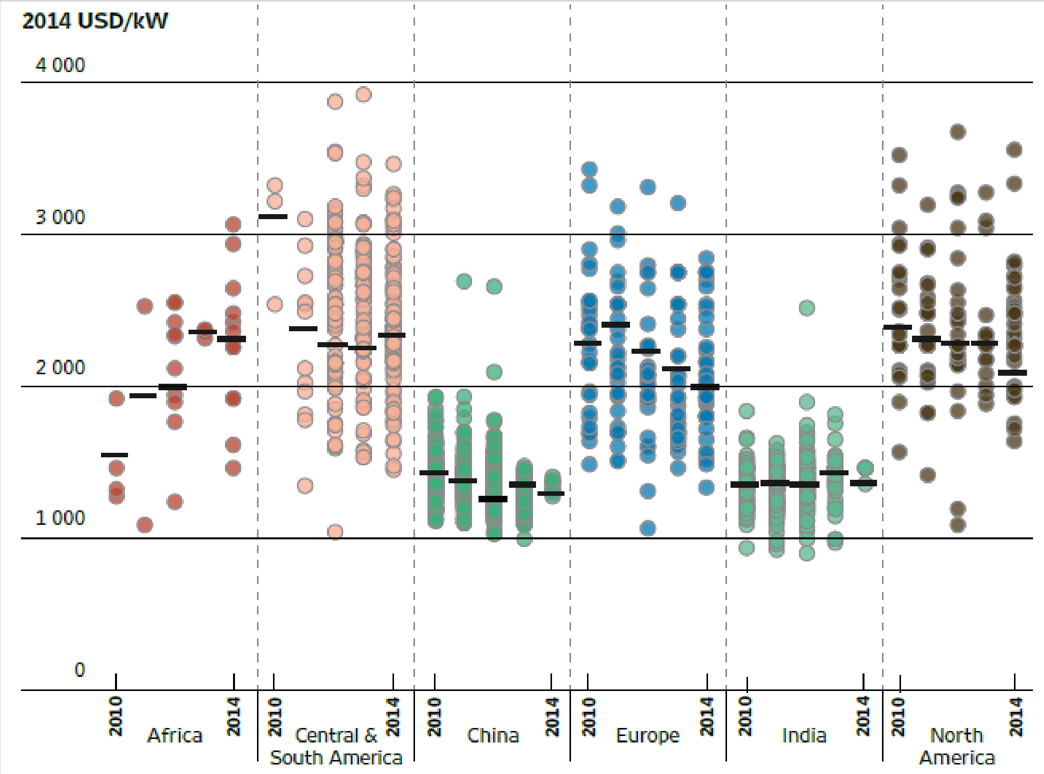


Figure 13 LCOE of commissioned and proposed wind projects (> 5 MW) in 2013/14 per region



Source: IRENA (2015), Figure 4.18

Figure 14 Installed cost of commissioned and proposed wind projects (> 5 MW) in 2010/14 per region



Source: IRENA (2015), Figure 4.6

2.4 Concentrated solar power

Concentrating solar power (CSP) is a power generation technology that uses mirrors to concentrate the sun's rays and, in most of today's CSP systems, to heat a fluid that is used to produce steam. Parabolic trough collectors (PTC) dominate the total installed capacity of CSP plants at about 4.0 GW installed capacity in 2012 (WEC 2013). Installed capacity of power and heliostat technology was about 0.8 GW. Spain and the USA play host to the most important CSP markets (4.8 MW in 2014, up from 1.8 MW in 2000), but China and India, as well as Morocco and South Africa, are both developing and financing a number of plants.

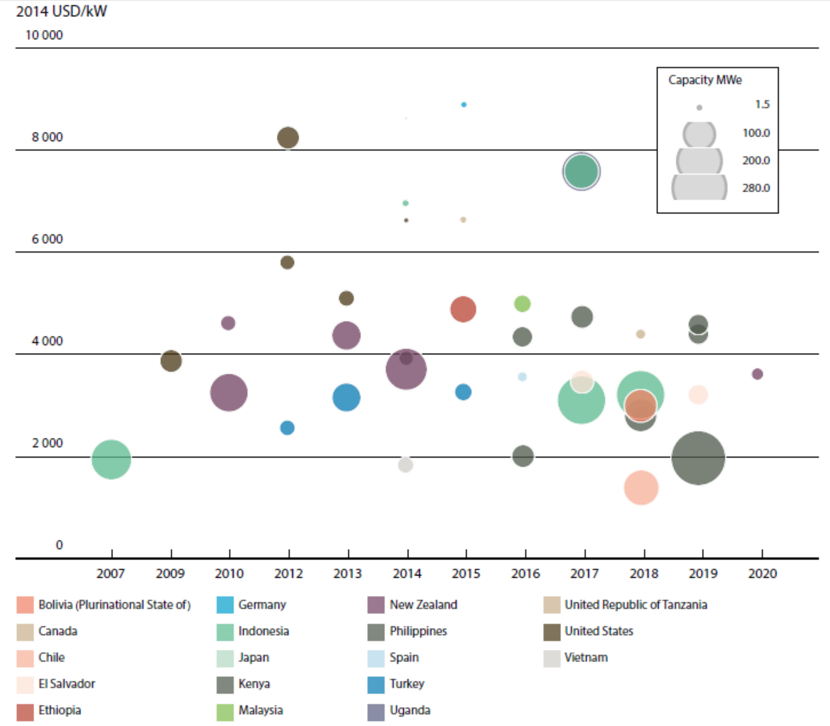
Cost quoted in 2010/13 vary between USD 3420-7670/MW for systems without storage and (at capacity factors 24-28%) LCOE of USD 0.20-0.50/kWh USD 0.123-0.248 in China/India)[1]. CSP can integrate low-cost thermal energy storage in order to provide dispatchable electricity to the grid and capture peak market prices. Investment costs with storage in 2010/13 were about USD 6000-11,000/MW and (at capacity factor 28-42%) LCOE of USD 0.16-0.47/kWh. The weighted average LCOE of CSP by region varied from a low of USD 0.20 in Asia to a high of USD 0.25/kWh in Europe in recent years, with the LCOE of individual projects varying significantly depending on location and level of storage. However, as costs are falling, recent projects are being built with LCOEs of USD 0.17/kWh, and power purchase agreements are being signed at even lower values where low-cost financing is available. Future cost reductions can be expected if deployment accelerates, but policy uncertainty is hurting growth prospects.

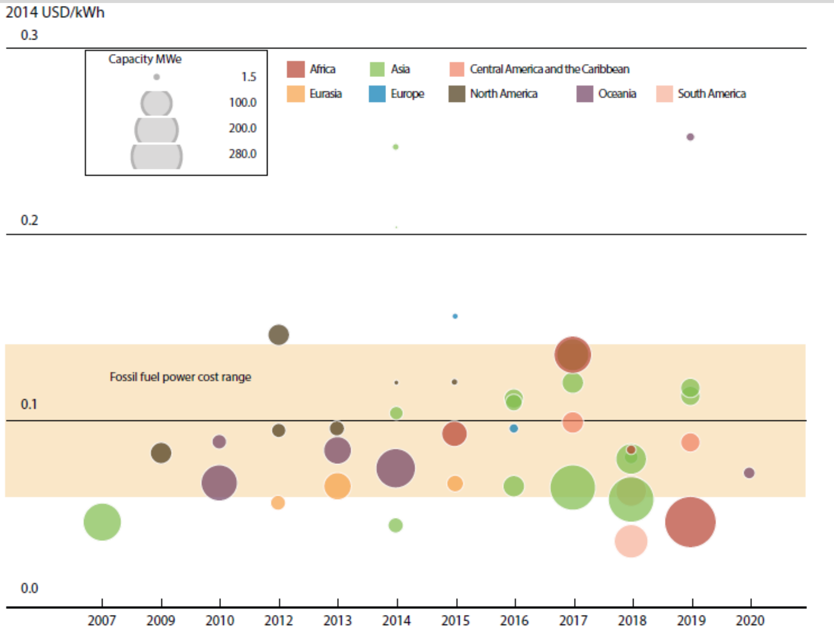
[1] Assuming a 25-year economic lifetime

2.5 Geothermal energy

Geothermal energy holds enormous potential for power generation and other applications drawn sustainably from a renewable resource. World primary energy consumption was 560 EJ in 2012 (or 155,505 TWh; GEA, 2014), final consumption was 104,426 TWh, of which 18,608 TWh electricity. The IPCC Special Report estimates that the global geothermal potential is in the same order or magnitude of about 118 EJ per year (to 3km depth) up to 1109 EJ/yr (up to 10 km depth) as annual global energy

Figure 15 Installed capacity cost and levelised cost of geothermal energy (2014)





Source: IRENA (2015), Figures 9.2 and 9.5. LCOE assumes 25 yrs economic life, O&M cost of USD 110/kW/yr demand. For comparison, the (REN21 2016) output in 2015 of geothermal energy was rather modest, 75 TWh as electricity and 75 TWh as heat. Currently, installed capacity is about 13.2 GW and another 12.5 MW is under development by various countries in over 700 sites.

Geothermal energy is traditionally extracted from in areas near the edges of tectonic plates where high-temperature hydrothermal resources are available near the surface Where the hydrothermal resource is available, geothermal electricity is generally cost effective and competitive, typically providing baseload generation, thus not requiring load-balancing equipment. Like other renewable energy sources, initial investment cost is high (about USD 1080/1800 to 6000/8000/kW), but levelised cost (USD 0.04-0.14/kWh up to USD 0.28/kWh) can be low. Between 2007 and 2014, the LCOE of geothermal varied from as low as USD 0.04/kWh for second-stage development of a field to as high as USD 0.14/kWh for greenfield developments. Plants require no fuel and O&M cost are low and can range from USD 0.01-0.04/kWh; IPCC, 2011, chapter 4; and IEA, 2011; IRENA, 2015; WEC, 2013). Total installed costs appear to have stabilised, but Projects that are planned for the period 2015 to 2020 expect to be able to reduce installed costs with about 7% by 2020 due to better drilling technology and higher capacity factors (from 85-95% on average).

2.6 Ocean energy

Ocean energy (also referred to as marine energy) holds enormous potential for power generation and other applications drawn sustainably from a renewable resource. By the end of 2014, installed capacity of all ocean energy technologies was only 530 MW, of which the bulk (500 MW) in two tidal range facilities (in Brittany, France, and Sihwa, Rep. of Korea; REN21, 2016). This is indicative for both the technological maturity *of tidal range power* (the only ocean energy technology that can be classified with 'high' technology readiness; other technology more in the prototype stage) and also its strong limitations (only a few applications due to high capital cost, limitation to specific locations, and the environmental consequences, similar to the dams in hydropower). A commercial market for ocean energy technologies has not really developed yet. *Wave and tidal stream energy technologies* are considered on the next level in terms of technology readiness (i.e. 'moderate', see Annex 2) and have attracted some commercial interest with a small number of pilot grid-connected devices installed. A few *OTEC (ocean thermal energy conversion)* demonstration plants have been installed, while ocean current and salinity gradient technology have remained in the research and development stage.

Most data come from a few pilot projects and thus have a large margin of error, but given the pre-commercial or pilot stage, ocean technology have high cost (LCOE) that are intrinsic to their early development stage (see Table 4).

Table 4 Estimates of investment and levelised cost of hydropower

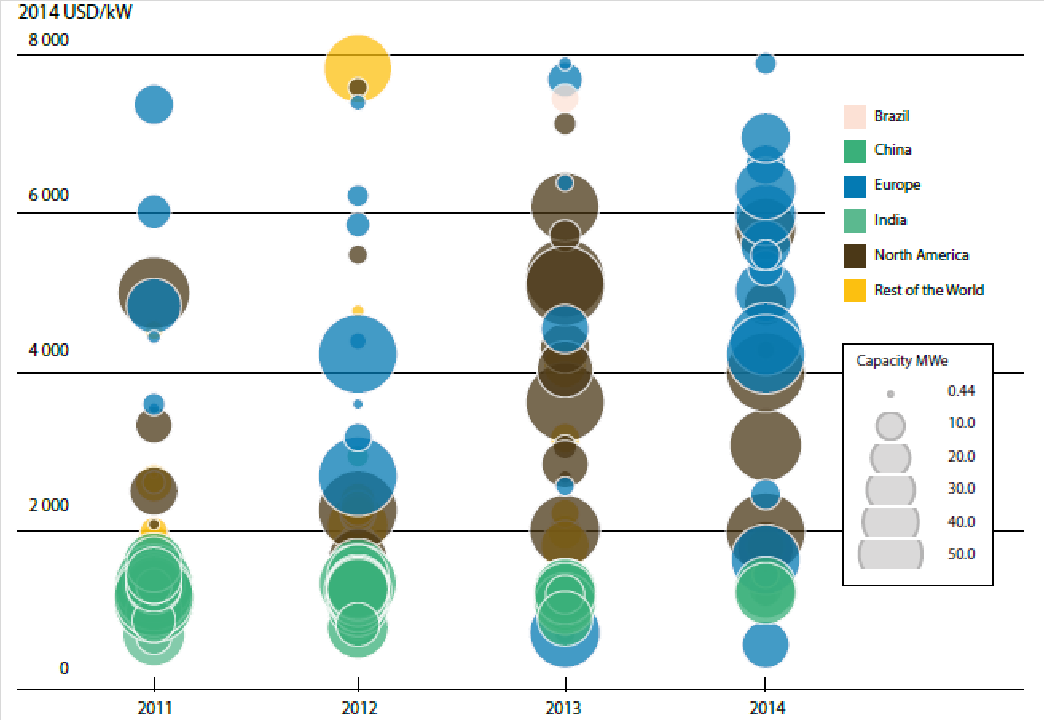
	Design life (years)	Investment cost CAPEX $/kW	O&M cost OPEX $/kW	Capacity factor (%)	LCOE ($/MWh)
Tidal range	40	4,500-5,000	100	22.5-28.5	
Tidal current	20				
- first pilots (0.3-10 MW)		5,100-14,600	140-1,160	26-40	260-1050
- first commercial 2020-30 (3-90 MW)		3,300-5,600	90-400	35-45	130-280
Wave	20				
- first pilots (1-3 MW)		4,000-18,100	140-1,500	25-40	284-1058
- first commercial 2020-30 (2-75 MW)		2,700-9,100	70-380	35-40	120-470
OTEC	20				
- first pilots (0.1-5 MW)		12,000-45,000	800-1,440	97	150-280
- first commercial 2020-30 (100 MW)		7,000-13,000	340-620		

Compiled from IRENA (2014), table 1 and IPCC (2012), table 6.3; WEC (2013)

2.7 Biomass for power

Bioenergy draws on a wide range of potential feedstock materials: forestry and agricultural residues and wastes of many sorts, as well as material grown specifically for energy purposes. The raw materials can be converted to heat for use in buildings and industry, to electricity, or into gaseous or liquid fuels, which can be used in transport, for example. This degree of flexibility is unique amongst the different forms of renewable energy.

Figure 16 Total installed costs of biomass-fired power generation, 2011-14



Source: IRENA (2015), Figure 8.6

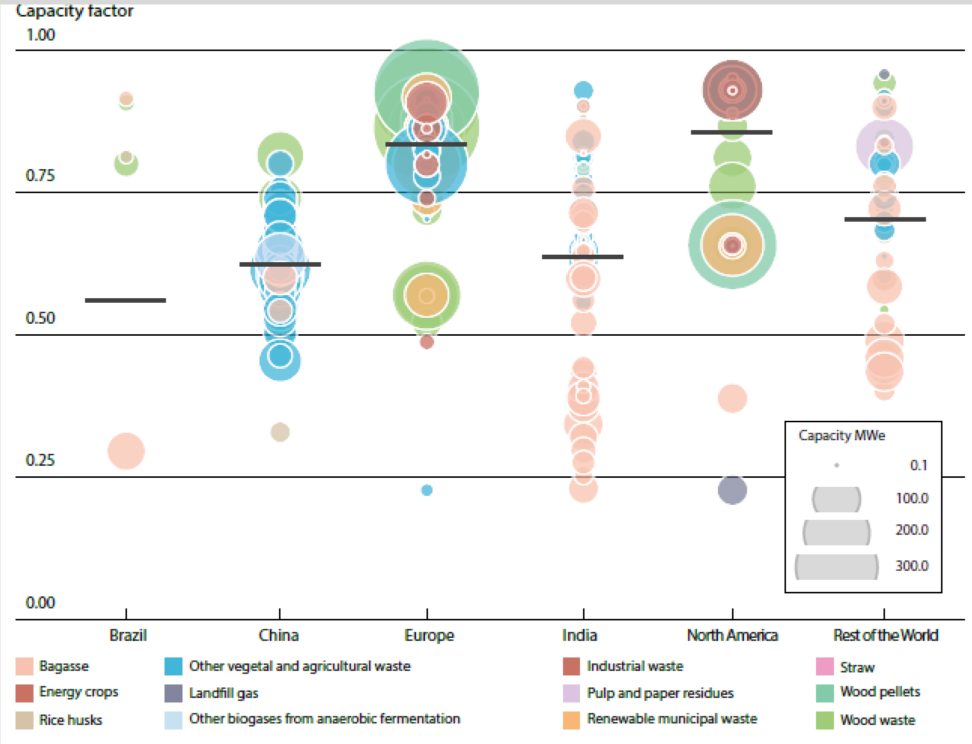
Bio-power capacity was an estimated 106.4 GW in 2015 (up from 68 GW in 2010), and generation 464 TWh (REN21 2015). The leading countries for electricity generation from biomass in 2015 were the United States (69 TWh), Germany (50 TWh), China (48 TWh), Brazil (40 TWh) and Japan (36 TWh) followed by the United Kingdom and India.

Table 5 Estimates of investment and levelised cost of biomass-fired power

Bio-power technology and feedstock	Typical plant size	Conversion efficiency	Capacity factor	Capital cost (USD/kW)	LCOE (USD/kWh)
Gasification	1-40 MW 0.2-5 MW	30-40%	40-80%	2050-5500	0.06-0.24 0.08-0.12
Bio-methanation (anaerobic digestion) - Large - Small - Landfill gas	1-20 MW	25-40%	50-90%	500-6500 600-900 1900-2200	0.06-0.19 - 0.04-0.095
Bio-power from solid biomass - Co-firing with coal - With MSW (municipal solid waste)	1-200 MW	25-35%	50-90% 60-90%	800-5400 200-800	0.05-0.20 0.04-0.12 0.034-0.095

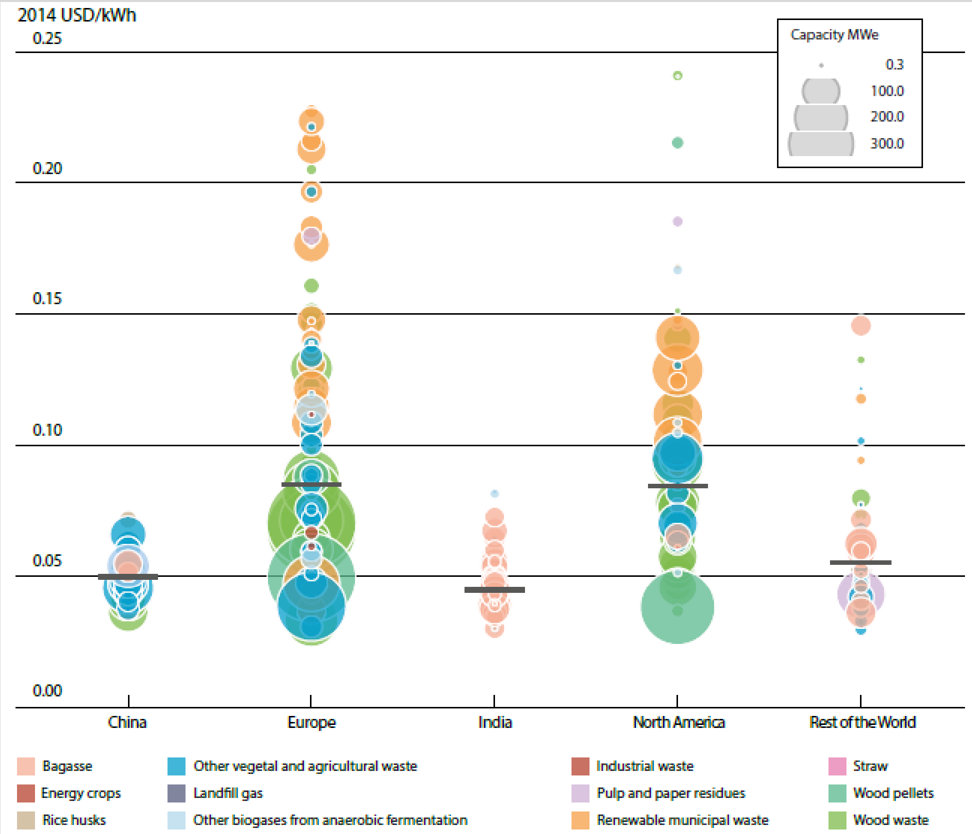
Compiled from IRENA (2014), table 1 and IPCC (2011), table 6.3; WEC (2013). Fixed O&M cost are typically 2-6% of CAPEX, while variable O&M cost are around USD 0.005/kWh.

Figure 17 Capacity factors of biomass-fired systems per country/region



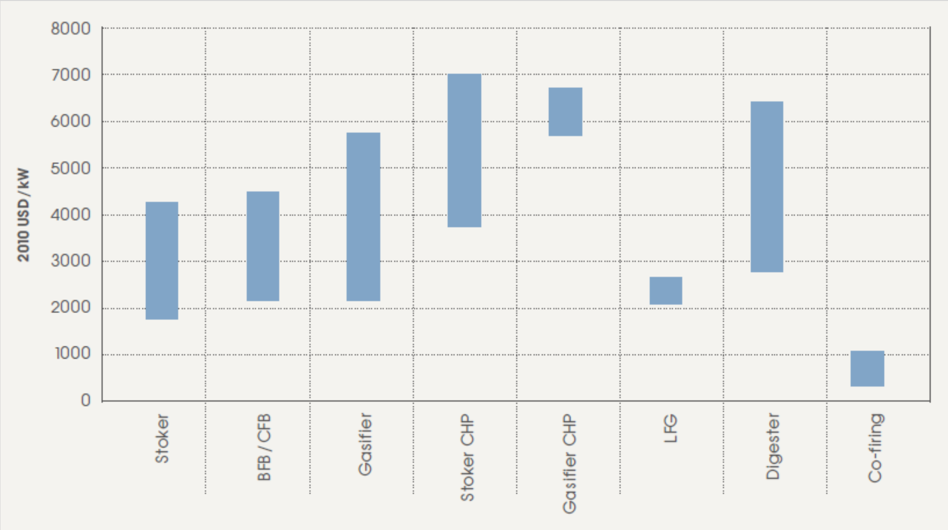
Source: IRENA (2015), Figure 8.7. Technically, it is possible for biomass-fired electricity plants to achieve capacity factors of 85% to 95%. In practice, most plants do not regularly operate at these levels. Feedstocks may be a constraint on capacity factors in cases where systems relying on agricultural residues may not have year-round access to low-cost feedstock and buying alternative feedstocks might make plant operation uneconomical

Figure 18 LCOE of biomass-fired systems per country/region



Source: IRENA (2015), Figure 8.8

Figure 19 Installed capital cost ranges by bio-power technology



Source: IRENA (2012), Vol. 1/5 (biomass), Fig. 5.3, 6.2 and 6.3

Figure 20 Cost ranges for bio-power technologies

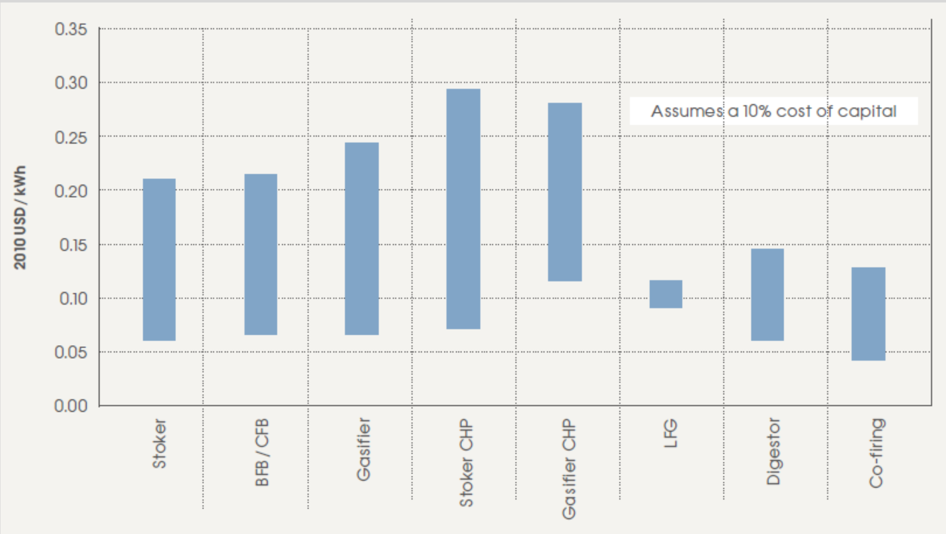
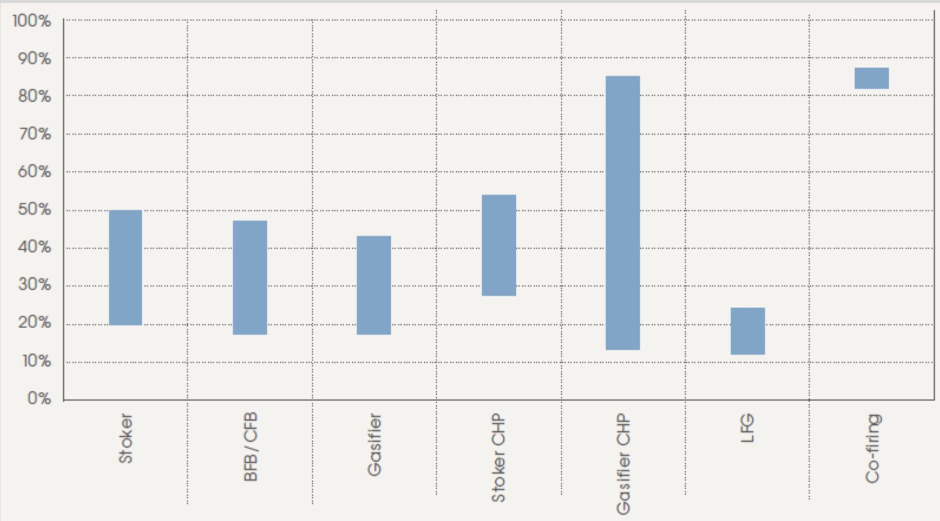


Figure 21 Share of fuel cost in bio-power generation fort high and low feedstock prices



The wide range of biomass-fired power generation technologies and feedstock costs translates into a broad range of observed LCOE of biomass-fired electricity, as presented in the Table 5 and Figure 18. Most biomass power generation technologies are mature and biomass and can be competitive at agricultural and forestry sites where low-cost feedstocks and handling facilities are available to keep feedstock and capital costs low. Where this is not the case, or where these feedstocks need to be supplemented by additional feedstocks (e.g. outside seasonal harvesting periods), then competitive supply chains for feedstocks are essential for making biomass-fired power generation economically sound (IRENA, 2015). Feedstock costs can be zero for some wastes, including those produced onsite at industrial installations, such as black liquor at pulp and paper mills or bagasse at sugar mills.

Biomass can provide dispatchable baseload electricity at very competitive costs. The regional or country weighted LCOE ranged from a low of USD 0.04/kWh in India and USD 0.05/kWh in China to USD 0.085/kWh in Europe and North America over the last ten years. Individual projects typically generate electricity that costs between USD 0.03 and USD 0.14/kW. But higher values exist, up to USD 0.25/kWh, particularly for waste incineration projects in the OECD where the primary purpose of the process is not electricity generation, but waste disposal (IRENA, 2015).

2.8 Fossil fuels and nuclear

The economics of conventional thermal generation projects differ substantially from those of intermittent, low marginal cost renewables such as solar and wind. Regionally, the largest differentiator between conventional coal and gas projects tends to be the cost of input fuels, which are highly localised. For nuclear projects upfront capital costs are high enough that fuel becomes less of a cost differentiator. The importance of fuel costs is shared by biomass facilities, but not by most other renewable types as once a renewable project is up and running the marginal cost of generation is minimal (WEC, 2013).

Table 6 Levelised cost of coal, gas and nuclear

	Capital cost (CAPEX) (USD/MW)	OPEX (USD/kW/yr)	Capacity factor (%)	LCOE (USD/kWh)
Coal	660-3700	30.6-76.5	80-98%	0.035-0.172
Gas (combined-cycle turbines)	760-1510	14.6-58	78-83%	0.061-0.148
Nuclear	3570-6520	56-123	85-92%	0.091-0.147

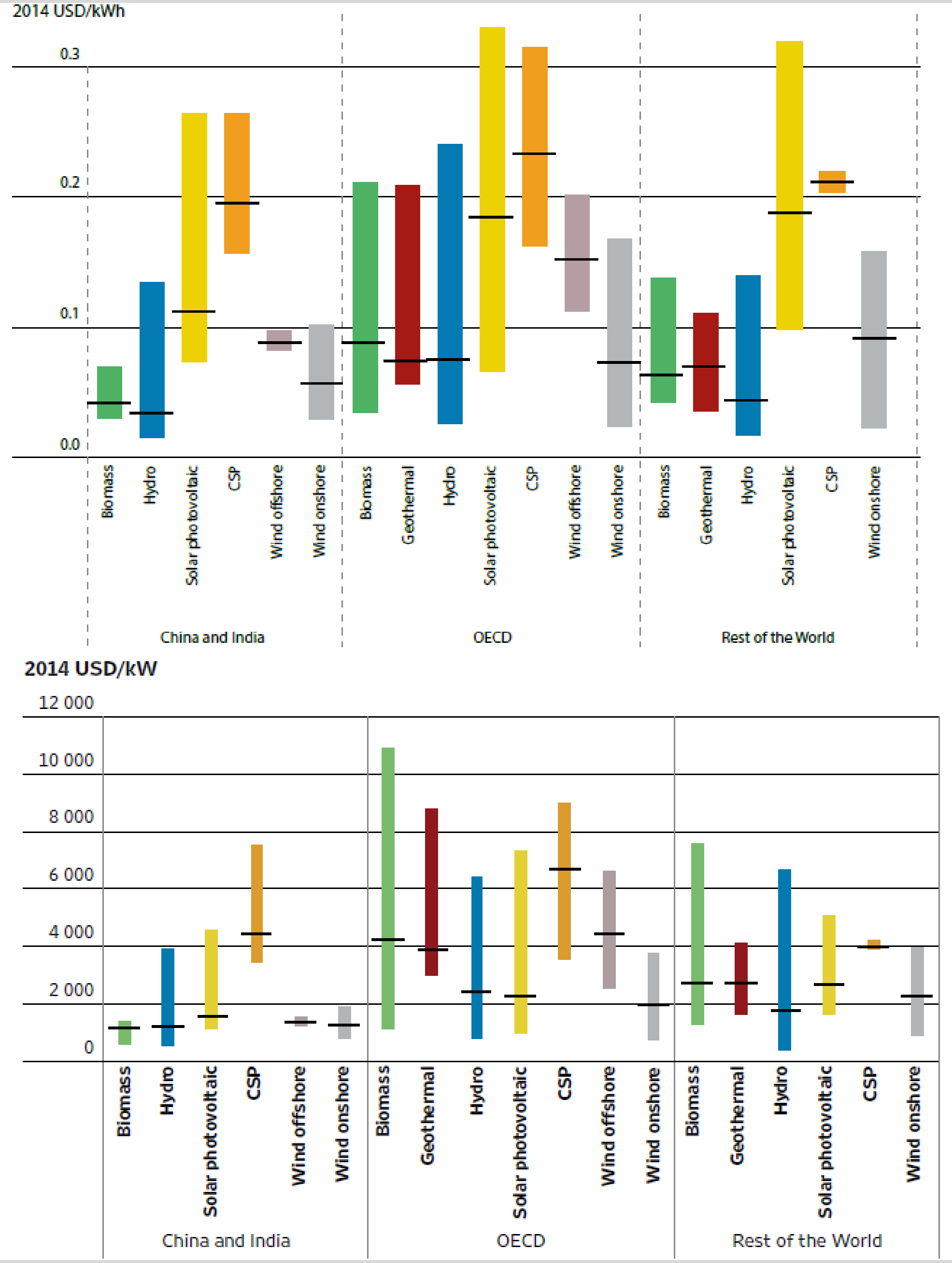
Compiled from WEC (2013). The ranges vary per region and prices of fuels and do not necessarily reflect maximum or minimum vales

3. COST COMPARISON OF POWER GENERATION TECHNOLOGIES

3.1 Utility-scale renewable energy technologies

Biomass for power, hydropower, geothermal and onshore wind can all now provide electricity competitively compared to fossil fuel-fired power generation. In particular, the levelised cost of electricity (LCOE) of solar PV has halved between 2010 and 2014, so that solar photovoltaics (PV) is also

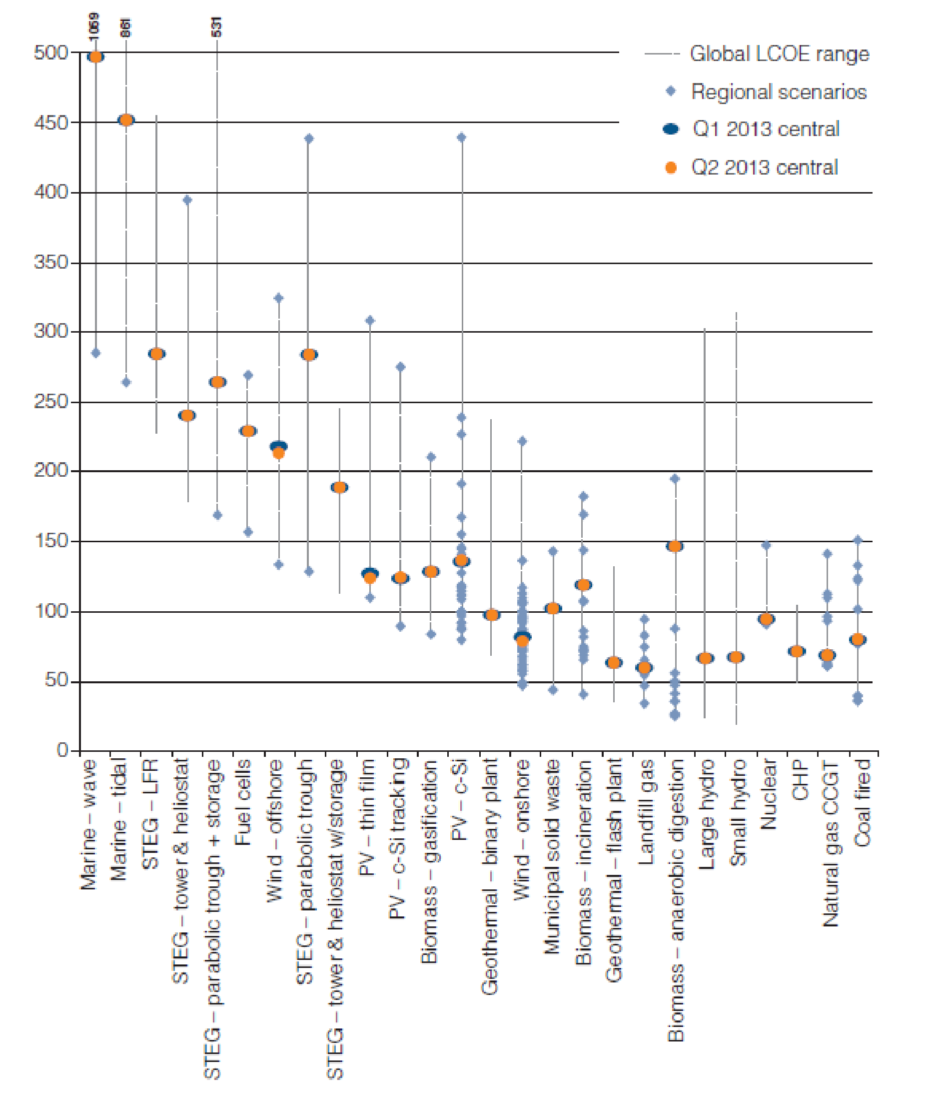
Figure 22 Levelised cost and installed costs of electricity from renewable energy (2013-14)



Source: IRENA (2015), Figures ES.1 and 2.7

increasingly competitive at the utility scale. Typically, the more mature technologies of onshore wind and solar PV are accepted as relatively low risk and gain more favourable financing terms. The story of increased competitiveness, however, remains a nuanced one. For technologies that are widely deployed across the globe, such as onshore wind, crystalline silicon PV and hydropower, there are significant cost variations between regions. Also, a key component in the LCOE of renewable technologies is the cost of finance and this varies by technology and location. The financing of offshore wind projects however is still highly project specific, depending on the distance from shore, construction technology used and experience of the developer (WEC, 2013; IRENA, 2016).

Figure 23 Levelised cost of energy technologies (2013)



Source: WEC (2013), Fig. 3

Table 8 Typical cost of power generation in good African conditions (2010)

	Investment cost	Capacity factor	Fuel cost	Electricity price[1]	Transmission and distribution cost
	(USD/kW)		(USD/GJ)	(US cents/ kWh)	(US cents/kWh)
Solar PV grid connected (85%PR)	3,000-4,000	0.2		24-37	3-7
Solar PV no battery	3,500-4,500	0.2		30-47	
Solar PV with battery (2.4 kWh/kW)[2]	5,000-6,000	0.2		45-65	
CSP grid connected no storage (90% PR)	5,500[3]	0.3-0.4		35-47	3-7
CSP grid connected 8 hrs storage (90% PR)	8,500	0.5-0.7		31-43	3-7
Large hydropower (above 10 MW)	1,000-2,000	0.5		4.5-9	3-7
Small hydropower (0.1 to 10 MW)	2,000-4,000	0.5		9-18	1-2
Pico hydropower Below 0.1 MW	4,000-8,000	0.5		18-36	1
Onshore wind (2 MW)	1,750[4]	0.25-0.40		10-16	3-7
Onshore wind (0.2 MW)	3,000	0.2-0.25		27-34	3-7
Biomass (bagasse boiler)	2,500	0.5	0.5-3	12-15	3-7
Biomass co-combustion in coal-fired power plant	1,250	0.75	1-5	5-9	3-7
Geothermal (high quality resource)	5,000[5]	0.8		14	3-7

[1] *Assumes 15% annuity plus 5% O&M. Excludes inflation and taxes/subsidies.*

[2] *Given a 20% capacity factor, a 1 kW panel produces 1,740 kWh. If half of the electricity is stored, evenly divided over the days of the year, 2.4 kWh of daily storage is needed. If battery discharge is limited to 25%, 10 kWh of battery storage capacity is needed. For deep-cycling lead acid batteries this costs USD 1,500.*

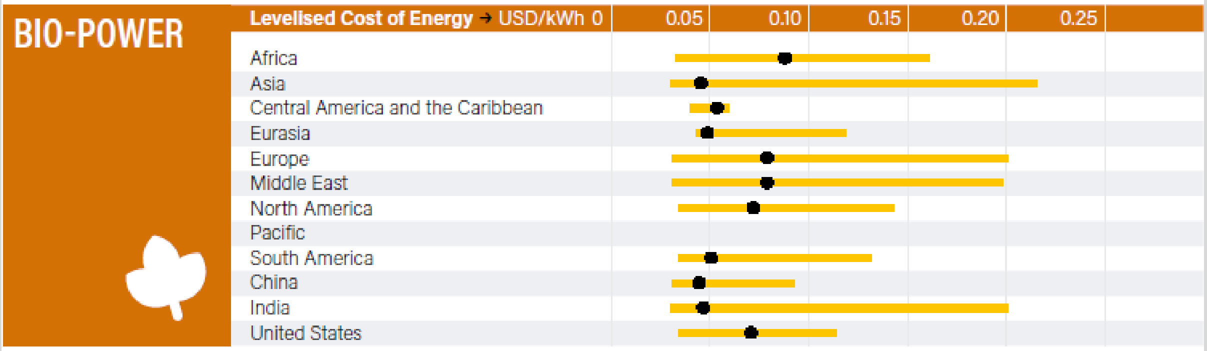
Source: IRENA (2012), Prospect for the African Power Sector

Table 7 Estimated LCOE (average of regional values in USA) for generation plants entering service in 2022

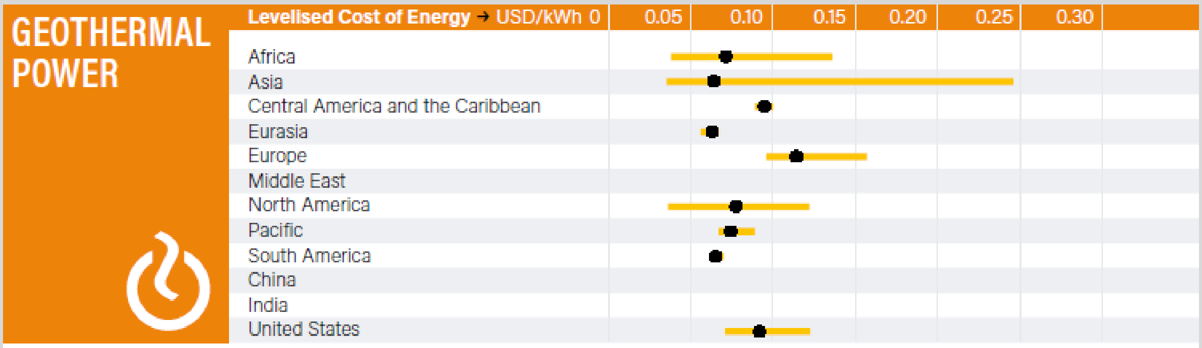
		U.S. Average LCOE (2015 $/MWh) for Plants Entering Service in 2022				
Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System LCOE
Dispatchable Technologies						
Advanced Coal with CCS[2]	85	97.2	9.2	31.9	1.2	139.5
Natural Gas-fired						
Conventional Combined Cycle	87	13.9	1.4	41.5	1.2	58.1
Advanced Combined Cycle	87	15.8	1.3	38.9	1.2	57.2
Advanced CC with CCS	87	29.2	4.3	50.1	1.2	84.8
Conventional Combustion Turbine	30	40.9	6.5	59.9	3.4	110.8
Advanced Combustion Turbine	30	25.8	2.5	63.0	3.4	94.7
Advanced Nuclear	90	78.0	12.4	11.3	1.1	102.8
Geothermal	91	30.9	12.6	0.0	1.4	45.0
Biomass	83	44.9	14.9	35.0	1.2	96.1
Non-Dispatchable Technologies						
Wind	40	48.5	13.2	0.0	2.8	64.5
Wind – Offshore	45	134.0	19.3	0.0	4.8	158.1
Solar PV[3]	25	70.7	9.9	0.0	4.1	84.7
Solar Thermal	20	186.6	43.3	0.0	6.0	235.9
Hydroelectric[4]	58	57.5	3.6	4.9	1.9	67.8

Source: EIA Energy Outlook (2016), LCOE data

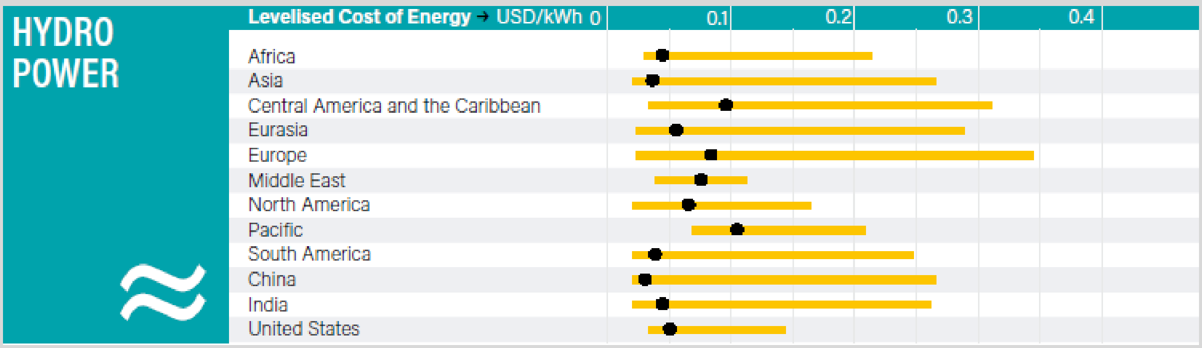
Table 9 Investment costs and LCOE of RE technologies for power supply



Investment Cost → USD	min	max	wa	Capacity Factor → %	min	max	wa
Africa	625	5579	● 1654		0.454	0.913	● 0.618
Asia	536	6082	● 1486		0.202	0.95	● 0.623
Central America and the Caribbean	534	7805	● 1021		0.225	0.796	● 0.317
Eurasia	1344	7106	● 1756		0.713	0.958	● 0.831
Europe	507	7957	● 3249		0.228	0.933	● 0.835
Middle East	885	4272	● 2895		0.291	0.929	● 0.566
North America	510	7641	● 3584		0.228	0.958	● 0.847
Pacific	3852	3851	● 3851		0.508	0.506	● 0.507
South America	547	7885	● 1662		0.206	0.942	● 0.531
China	542	6082	● 1576		0.206	0.95	● 0.618
India	536	5497	● 1112		0.202	0.976	● 0.626
United States	1062	7641	● 4076		0.891	0.958	● 0.93

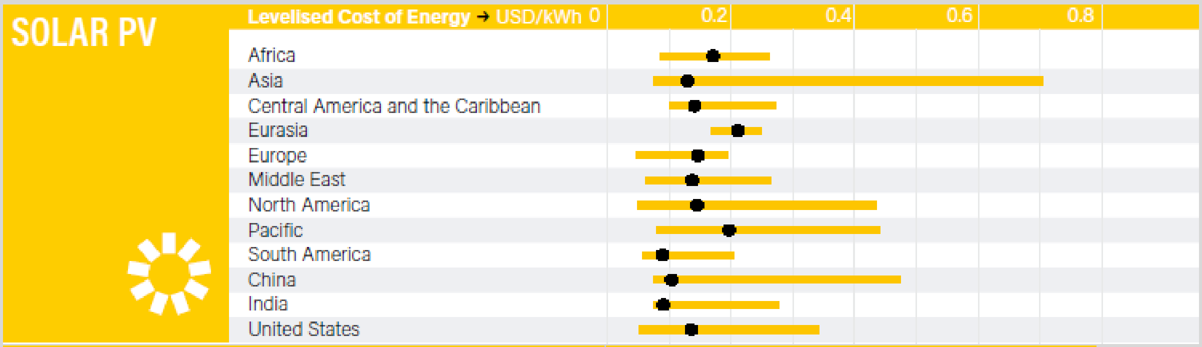


Investment Cost → USD	min	max	wa	Capacity Factor → %	min	max	wa
Africa	1719	7689	● 3818		0.8	0.92	● 0.84
Asia	1514	8736	● 3148		0.411	0.929	● 0.83
Central America and the Caribbean	3260	3537	● 3413		0.57	0.6	● 0.58
Eurasia	2613	3278	● 3113		0.8	0.8	● 0.8
Europe	3613	8919	● 5209		0.6	0.8	● 0.66
Middle East							
North America	2029	8353	● 5017		0.74	0.923	● 0.83
Pacific	3303	4676	● 3796		0.6	0.8	● 0.8
South America	3027	4348	● 3587		0.8	0.95	● 0.82
China	1501	9722	● 1943				
India	1501	7475	● 2169				
United States	2941	8353	● 5961		0.74	0.9	● 0.79

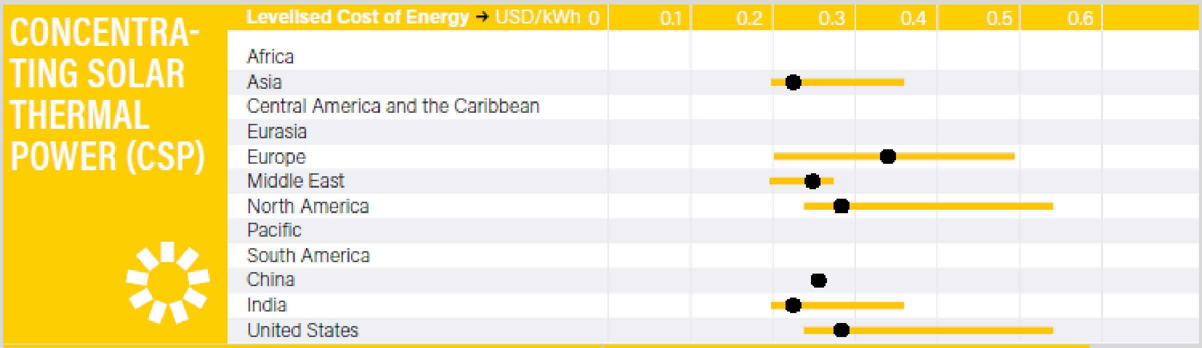


LCOE of RE technologies for power supply

Investment Cost → USD	min	max	wa	Capacity Factor → % min	max	wa
Africa	454	6730	● 1478	0.264	0.856	● 0.413
Asia	458	7553	● 1212	0.139	0.947	● 0.46
Central America and the Caribbean	674	5416	● 2945	0.25	0.8	● 0.476
Eurasia	519	5416	● 2945	0.169	0.854	● 0.421
Europe	528	7913	● 1790	0.140	0.713	● 0.353
Middle East	453	2186	● 1303	0.201	0.757	● 0.316
North America	723	7103	● 2252	0.184	0.89	● 0.509
Pacific	1780	4119	● 2984	0.241	0.614	● 0.504
South America	527	7211	● 1851	0.251	0.945	● 0.569
China	458	7220	● 1023	0.131	0.947	● 0.451
India	467	5759	● 1321	0.115	0.898	● 0.451
United States	723	6757	● 1384	0.31	0.779	● 0.398

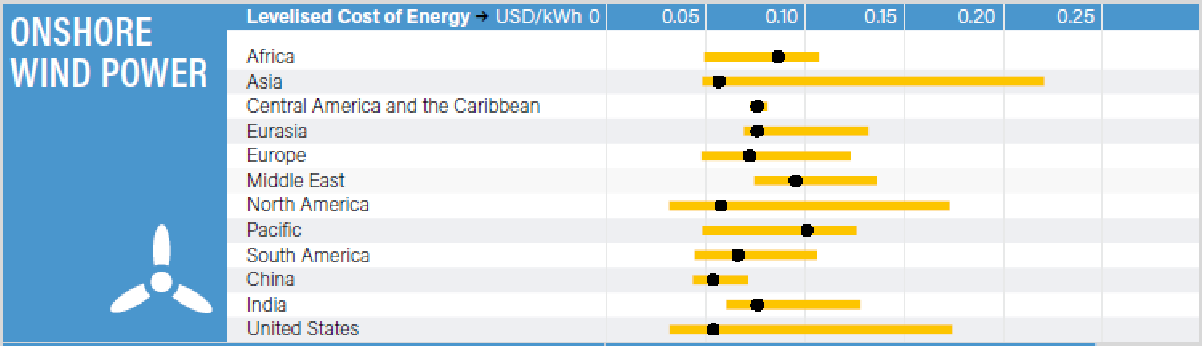


Investment Cost → USD	min	max	wa	Capacity Factor → % min	max	wa
Africa	944	4110	● 2649	0.016	0.278	● 0.199
Asia	819	7997	● 1624	0.101	0.247	● 0.166
Central America and the Caribbean	1600	4000	● 2076	0.155	0.227	● 0.198
Eurasia	1545	3697	● 2775	0.117	0.127	● 0.119
Europe	944	2827	● 1408	0.098	0.30	● 0.123
Middle East	1311	4000	● 2553	0.174	0.347	● 0.256
North America	800	5900	● 2365	0.095	0.336	● 0.196
Pacific	1180	7539	● 2857	0.114	0.271	● 0.191
South America	1132	4326	● 2249	0.130	0.404	● 0.320
China	998	7780	● 1439	0.101	0.184	● 0.170
India	833	4916	● 1403	0.159	0.247	● 0.206
United States	965	5900	● 2336	0.095	0.336	● 0.197

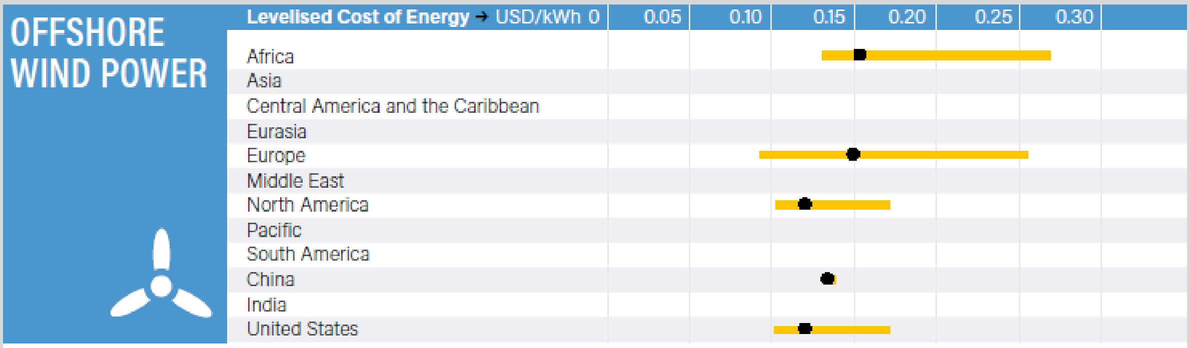


Investment Cost → USD	min	max	wa	Capacity Factor → % min	max	wa
Africa	10094	17402	● 14153	0.194	0.194	● 0.194
Asia	3501	13693	● 4423	0.17	0.535	● 0.275
Central America and the Caribbean						
Eurasia						
Europe	4811	17341	● 8839	0.148	0.631	● 0.308
Middle East	3491	4097	● 3705	0.194	0.263	● 0.22
North America	4714	9009	● 6794	0.18	0.405	● 0.299
Pacific	9735	10767	● 9829	0.21	0.21	● 0.21
South America						
China	3501	13639	● 3680	0.17	0.28	● 0.272
India	3539	7475	● 4328	0.206	0.535	● 0.276
United States	4714	9009	● 6794	0.18	0.405	● 0.299

LCOE of RE technologies for power supply



Investment Cost → USD	min	max	wa	Capacity Factor → % min	max	wa
Africa	1345	2848	● 2080	0.214	0.456	● 0.346
Asia	958	2784	● 1280	0.172	0.435	● 0.243
Central America and the Caribbean	1680	2600	● 2268	0.296	0.520	● 0.434
Eurasia	1550	2651	● 1751	0.272	0.35	● 0.344
Europe	1353	3652	● 1917	0.139	0.412	● 0.277
Middle East	1983	3148	● 2497	0.313	0.390	● 0.372
North America	1275	3181	● 1874	0.166	0.516	● 0.352
Pacific	1060	3752	● 2533	0.275	0.436	● 0.337
South America	994	2903	● 1871	0.257	0.534	● 0.426
China	1032	1553	● 1251	0.221	0.36	● 0.242
India	958	1625	● 1228	0.172	0.258	● 0.234
United States	1496	3000	● 1770	0.166	0.608	● 0.358



Investment Cost → USD	min	max	wa	Capacity Factor → % min	max	wa
Africa	2115	5055	● 2668	0.204	0.312	● 0.26
Asia						
Central America and the Caribbean						
Eurasia						
Europe	2053	6480	● 4207	0.27	0.554	● 0.36
Middle East						
North America	2251	5063	● 2972	0.32	0.363	● 0.33
Pacific						
South America						
China	2115	3061	● 2767	0.204	0.287	● 0.26
India						
United States	2250	5063	● 2972	0.32	0.363	● 0.33

Compiled from REN21 (2016)

3.2 Costs of electrification: grid extension and mini-grids

Rural electrification is the process of bringing electrical power to rural and remote areas. *On-grid rural electrification* refers to the extension of electricity distribution to rural areas through an electricity grid. Grid connexion is the most expected solution as it is supposed to provide more power and energy to the customers at a lower price. Off-grid options can be grouped in two types. *Mini-grid* (a.k.a. distributed or isolated grids) refers to a system where all or a portion of the produced electricity is fed into a small distribution grid not connected to the main/national grid system. A *standalone (individual)* power system is an off-grid system that supplies a single rural customer with one or several generator sources (hybrid system with diesel and/or various RE technologies).

Table 10 Characteristics of grid-connected, mini-grid and individual (stand-alone) systems

	Grid connected	Minigrid <50 MW/own consumption	Stand-alone systems/ Individual electrification systems	Productive use
Gas	- 1500 GW			> 1 GW Gas-fired CHP systems
Diesel		5-10 GW 50 000–100 000 systems		
Hydro	Large >10 MW 10 000– 50 000 systems >1000 GW	Small < 10 MW 100 000–150 000 systems 75 GW	Micro-hydro 0.1– 1 MW Pico-hydro <0.1 MW	
Wind	310 GW 250 000 turbines	Diesel-wind hybrid <1000 village/mining systems	Small wind turbines 0–250kW 806 000 turbines	Wind pumps > 500 000
Solar PV	50 GW/0.5 mln large systems >50 kW 80 GW/10-20 mln rooftop systems 1-50 kW	Diesel-PV hybrid <10 000 village systems	SHS <1 kW 5-10 mln systems	Solar lighting 5 mln; Telecom towers 10 000; Solar water pumps; PV Fridges/refrigeration; Street lighting systems; Traffic signs; Phone recharging stations;
Biogas/ biodiesel to power	14 GW 30 000–40 000 systems	< 100 kW biogas plants > 1 million biogas systems Gasification/rice husk etc 1000–2000 systems		Livestock farms Back-up biodiesel generators
Biomass cogeneration	20 GW pulp, sugar/ethanol 1000–2000 systems 20–30 GW steam cycles/CH 1000–2000 systems 5–10 GW cofiring coal plant 250–500 systems			

Source: IRENA (2015), Off-grid Renewable Energy Systems

3.2.1 Grid extension

Grid extension is a network expansion from the national power transmission system to new areas and communities. The cost of extending lines to rural facilities can be prohibitively expensive. Costs of **high-voltage lines** are mentioned in various reports, but usually on a country basis. Some compilation is given below. Please note the difference between *build cost* (capital or infrastructure cost) and *lifetime cost* (build cost plus O&M cost).

Customers are connected through **medium to low voltage distribution** grids. Cost is often reported as cost per connection. *Grid densification* are new grid connection especially for households living close to the local utility grid but who are not yet connected. For grid densification by connecting to transformers (if villages which are located in close proximity to an existing transmission line will be connected) with change of voltage level costs are about EUR 800 as a rule of thumb, and for densification within an existing low-voltage distribution grid costs are EUR 750 per connection (TAF SE4All, 2015)

Table 12 Transmission lines

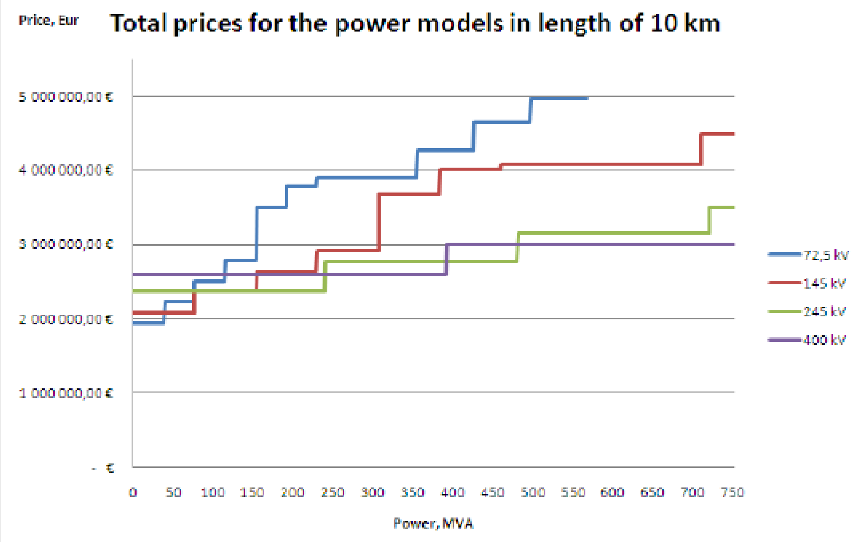
Source:	.
UK (Parsons, 2012)	400 kV AC overhead line: USD/km: 2.9- 5.5 million (lifetime); 1.7-2.6 (build cost) • 1390 MVA: USD 910-975/MVA-km (lifetime power transfer cost/km) • 6380 MVA: USD 820-860/MVA-km (lifetime PTC/km) Underground; USD/km: 13.3-26.5 million per km (lifetime); 12.0-23.5 (build cost) HVDC (subsea): USD 16.0-38.1 per km (converted at GBP = 1.3 USD, 2016)
Hannuksela (2011, Finland)	
TAF SE4All (2015, 2015/16)	*Assessment of PIDA projects* (E&S Africa (based on Central African interconnection and North-South Power Transmission Corridor DC). Average 1.258 million per km (incl. the AC/DC conversion stations). *Other data:* Note that prices depend a lot on rated power, copper prices (transformers), steel prices (overhead lines/towers), aluminium prices (overhead lines/conductors), local environment (lines, switchgear) and local price politics of equipment suppliers: • Cost of 220kV/800A (300MVA) overhead line is approximately 200,000 Euro per km for a double circuit line (2 x 300MVA) and approximately 120,000 Euro per km for a single circuit. Both for 'easy' terrain and note that this is a very low capacity for an interconnector; • 3 MVA transformers for 66/11kV are on the small side, but should cost around 200,000 Euro, 12 MVA: 300,000 Euro; • Switchgear per circuit breaker bay: 66kV: 200,000 Euro/bay; 11kV: 30,000 Euro/bay. Some country data: Mauretania (1 circuit) / Senegal (EUR million per km): 0.38; Cote d'Ivoire/Ghana/Burkina Faso (single/double): 0.38-0.39; Nepal: 2.00 and Paraguay: 0.67
Italy (Khandelwal, Pachori 2013)	Overhead (EUR million per km): - 380 kV: 0.60, 220 kV: 0.385; 132 kV: 0.295 Underground: - 380 kV: 3.5, 220 kV: 2.2; 132 kV: 1.875

Table 11 Electricity infrastructure cost

USD million per km	Underground	Overhead lines		
380-400 kV (2 circuit)	4.91 (3.56-5.90)	1.06 (0.58-1.40)	Substations	EUR 38.7k (26.4k-52.1k) per MVA EUR 42.6k (25.0k-55.5k) per kV
380-400 kV (2 circuit)		0.60 (0.30-0.77)	HVDC converter station	
220-225 kV (2 circuit)	3.31 (3.98-4.11)	0.41 (0.35-0.46)	1-4 converter	EUR 87.1k (76.0k-103.6k) per mVA
220-225 kV (1 circuit)	2.22 (1.92-2.44)	0.29 (0.16-0.30)	6-8 converter	EUR 155.7 (145.0k-173.3k) per MVA
Subsea cables: - AC: 1.14 (1.10-1.25) - DC: 0.76 (0.71-0.79)				Note (in Netherlands): 110 kV transmits 60-250 MVA 220 kV transmits 5000-1000 MVA 380 kV transmits 1200-1600 MVA

Source: Electricity infrastructure cost (ACER, 2015)

Table 13 Cost per connection of distribution networks

Country	Cost per connection (USD)	Country	Cost per connection (USD)
Benin	*2000*	*South Africa*	*800*
Ghana	*5500*	*Vietnam*	*570*
Tanzania	*600-1100*	*Nicaragua*	*220-588*
Mozambique	*134*	*Bolivia*	*62*
Kenya		*Peru*	*90*

Source: McKInsey & Co (2015); EU TAF (2015; 2015/16); www.energypedia.info

The cost will depend much upon the population density in the areas to be electrified, as shown by the following example (taken from EU TAF Sustainable Energy Handbook (Module 5.2). The table below shows that for a locality at 10 km from the grid, connecting only 10 customers (average yearly consumption of 1440 kWh per customer) with a 25 KVA transformer (i.e. 20% of maximum number of customers for this transformer) will cost more than USD 4000 per connection (including financial costs) and an unaffordable distribution cost of around USD 0.30/kWh, while connecting 200 customers with a 200 kVA transformer (i.e. 50% of maximum number of customers for this transformer) will cost around USD 400 per customer with an affordable distribution cost of USD 0.03 /kWh.

		A	B	C	D
MV line length (km)		10	10	10	10
MV/LV transformer capacity (kVA)		25	50	100	200
Maximum number of customers		56	111	223	444
of which households		40	85	178	366
LV Line Length per customer (meter/cust.)		48	47	47	47
Unit economic cost (US$/customer)					
Connection rate,,,,,,,,,,,,	20%	4211	2315	1308	760
Connection rate,,,,,,,,,,,,	50%	1752	993	590	371
Connection rate,,,,,,,,,,,,	100%	932	553	351	242

3.2.2 Decentralised grids (mini-grids)

A mini-grid will basically include a power generator and a network to distribute the electricity to the accessible consumers, to avoid the high costs of extending the main grid to these isolated areas. Those consumers should then be distant from the main grid (e.g. over 5-20 km), fairly close to each other (e.g. < 150m or density > 50 customers/km²) and with sufficient load demand (>200kWh/year).

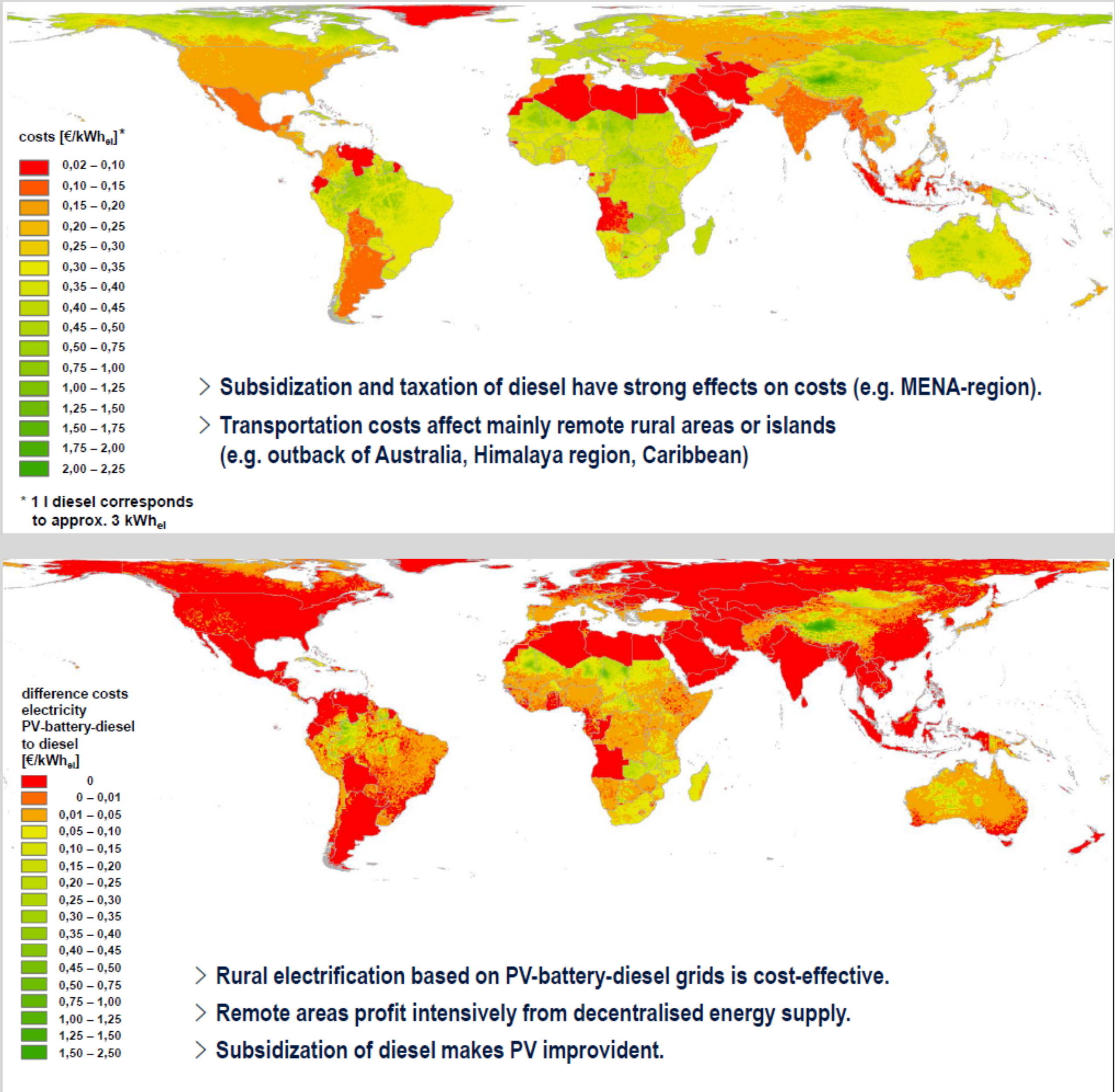
Table 14 Reference cost of mini-grid systems

Technology -based MG	Size range (kW)	Power plant investment ($/kW)	LCOE ($/kWh)	Operating time (h/yr)
Diesel genset	5 – 300	500 – 1500	0.3 – 0.6	On demand
Hydro	10 – 1000	2000 – 5000	0.1 – 0.3	3000 – 8000
Biomass-gasifier	50 – 300	2000 – 3000	0.1 – 0.3	3000 – 6000
Wind hybrid	1 – 100	2000 – 6000	0.2 – 0.4	2000 – 2500
Solar hybrid	1 – 150	5000 – 10000	0.4 – 0.6	1000 – 2000
MV distribution	*33kV*	*13,000 - 15,000*	*$/km (site specific)*	
LV distribution	*380V*	*5,000 – 8,000 $/km*	*A rough estimate of the required length is 30 customers per km.*	
Connection costs	*Ideally $350 per customer (but CAPEX/customer varies $350-3500)*			

Data compiled by TAF SE4All (2015/16), based on Green Mini-grids (IED, 2013) and IRENA Renewable Power Generation Costs in 2012 (2013)

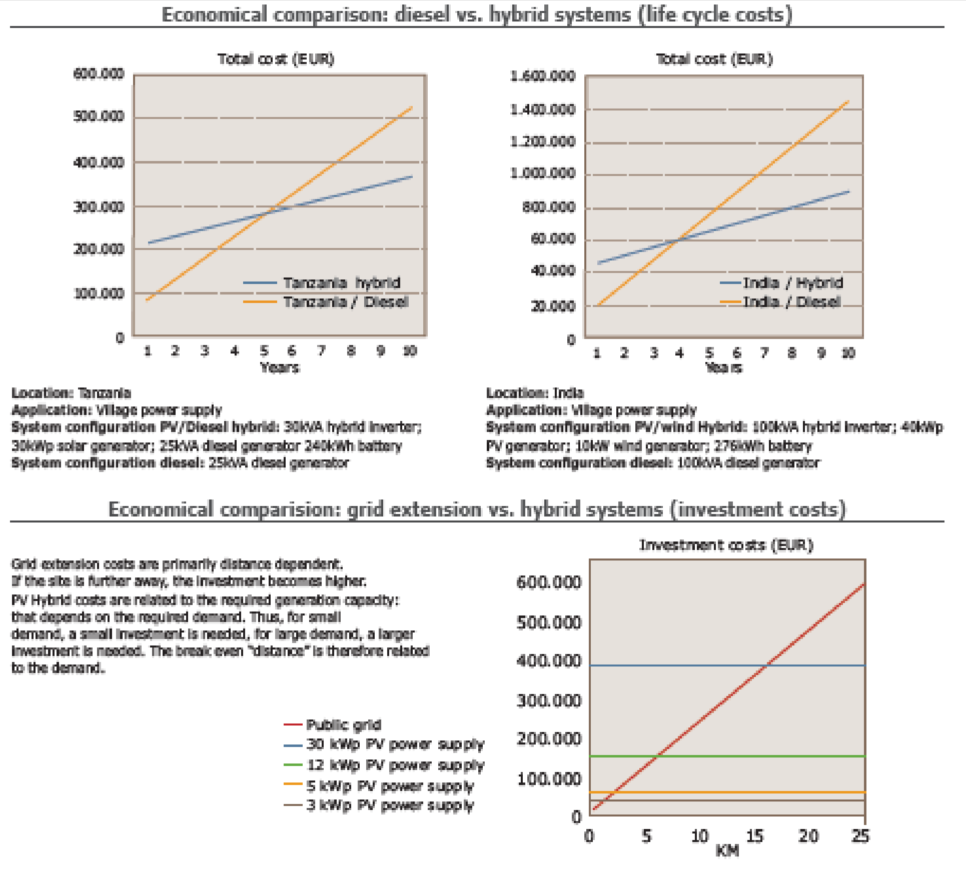
A limited number of publications have analysed the cost of renewable mini-grids. IRENA (2015) mentions costs of solar mini-grids of USD 0.43-0.71/kWh. As indicated in the table below, the cost varies per type of technology used and site location (operating time; load factor). As mini-grid systems RE systems often have batteries as storage, in future, investments cost may go down with the declining of advanced lead-acid. Increasingly, RE hybrid systems are increasingly becoming competitive in comparison with diesel-based grid systems. In many regions, payback periods of 5-7 years can be obtained with PV-hybrid mini-grids (see Figure 18 below).

Figure 24 Cost advantage of PV hybrid (diesel-battery) systems vs. diesel generators



Source: Paul Berthau, RLI (2014), *Global Market Potential for PV-based Mini-Grids in Developing Countries*

Figure 25 Examples, cost effectiveness of RE hybrid systems vs. diesel and vs. grid extension



Source: ARE brochure - *Hybrid power systems based on renewable energies*

3.2.3 Stand-alone systems

A standalone individual power system is an off-grid system that supplies a single rural customer with one or several generator sources (hybrid system) and various electrical appliances. According to the power dimension, they can be grouped into four categories: portable lights (i.e. rechargeable & solar lanterns), mini kits (i.e. pico hydro & pico solar systems), home systems (supplied by solar SHS or pico-hydro) and Residential Systems (generally supplied by hydro, wind or solar –with diesel backup or not). Most individual systems in the world are still supplied by diesel/fuel gensets.

Table 15 Costs of stand-alone PV systems

Technology	Description	Price range:
Solar portable	Single light source with/without mobile phone charging outlet; Entry level products with solar (PV) panels of 0.2-2 W	USD 20-60
Pico PV systems	Multi-lights source applications with mobile phone charging outlet made of a kit of components. Power range: 2-10 W	USD 150-200
Solar home systems (SHS)	Multi lights source applications with mobile phone charging outlet; Can power devices such as radio and TV. Power range: 10 W-250 W	USD 150-400
Residential home systems	12V systems replace diesel generators or car batteries. Can power multiple lighting points and devices as TV and fridges. Power range: 250 W-1,000 W	USD 400-1500

Cost data compiled by author

Table 16 The energy ladder and energy access

Rural electrification can be implemented through the 3 following options: 1. On-Grid rural electrification.
2. Distributed grid (mini-grid), 3. Stand-alone systems. For those populations and communities, the only way to get access to modern energy on a reasonable time scale is to implement off-grid solutions from the market adapted to the range of affordability. Individual off-grid solutions can empower the most remote communities to get a critical first step onto the **energy ladder** with basic energy services such as lighting, mobile phone charging, fans, TV, etc. Lighting and phone charging are the beginning not the end of energy access. Once these basic needs are met, many populations are capable of expanding their energy consumption to include higher level needs like refrigeration or even productive uses, such as agro-processing.

Energy access is not a simple question of 'having' or 'not having access'. The SE4ALL initiative by the United Nations is proposing use of multi-tier framework that recognizes the energy supply ladder, whereby a user's improved energy access leads to more demand for greater quantity and quality of energy. Tiers are based on the attributes of people's energy supply, and the services they use based on that supply. The indicative household electricity framework has six tiers: each defined by electricity supply attributes such as quantity, duration, evening availability, affordability, quality of supply, and legality of connection. A higher tier up the energy ladder represents an electricity supply with better attributes and the possibility of access to more modern energy services. The table below displays the average connection cost per customer according to the broad range of use on the energy ladder.

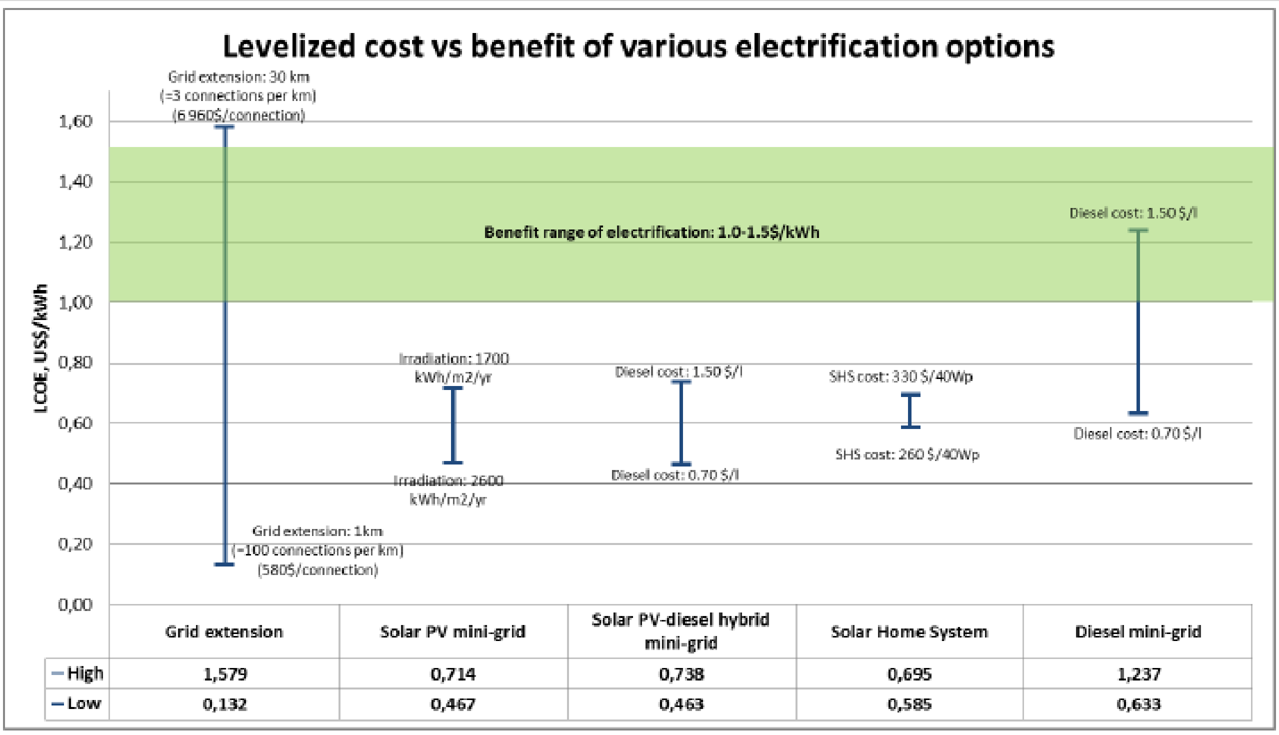
Continuous Spectrum of improving Electricity supply Attributes										
Attributes	Tier 0	Tier 1	Tier 1	Tier 1.5	Tier 2	Tier 2.5	Tier 3	Tier 3	Tier 4	Tier 5
Service Description	Kerosene lighting	Task lighting and phone charging (or radio)	Task lighting and phone charging (or radio)	4 lights, phone charging and radio	General lighting and TV or fan (if needed)	General lighting and TV and fan (if needed)	Tier 2 and any low power applicances	Tier 2 and any low power applicances	Tier 3 and any medium power applicance	Tier 3 and any high power applicances
Peak available capacity (W)	-	1	5	10	20	50	200	500	2000	2000
Duration (hours/day)	-	4	4	4	4	4	8	8	16	22
Evening supply (hours/day)	-	2	2	2	2	2	2	2	4	4
Average annual consumption per household										
Load factor		17%	17%	17%	17%	17%	18%	20%	20%	25%
annual consumption (kWh/year)		1,5	7,3	14,6	29,2	73	315	876	3504	4380
Price of electricity (US$/kWh)		5,0	4,8	4,0	4,0	3,0	1,0	0,50	0,30	0,25
annual cost (US$/year)		7,3	35	58	117	219	315	438	1051	1095
Average costs (US$/household)										
Least cost		70	110	166	288	500	1800	3200	1600	1600
Likely electricity supply technology	None		Solar lanterns		Stand-alone home systems		Mini grid		on grid	

Source: TAF SE4All (2015/16), based on ESMAP work (see e.g. ESMAP, 2015)

3.3 Cost comparison of electrification options

On-grid connections can be cost-effective for more dispersed populations living within a reasonable distance of transmission and distribution lines, even allowing for the additional expense of extending the service. The maximum economic distance for extending the grid tends to reduce over time, as the costs of generation in mini-grids or off-grid systems come down. beyond a certain distance, the costs of grid extensions become prohibitive, tipping the balance in favour of mini-grids or stand-alone systems.

Figure 26 NORPLAN study: Cost competitiveness of rural electrification solutions



Assumptions:

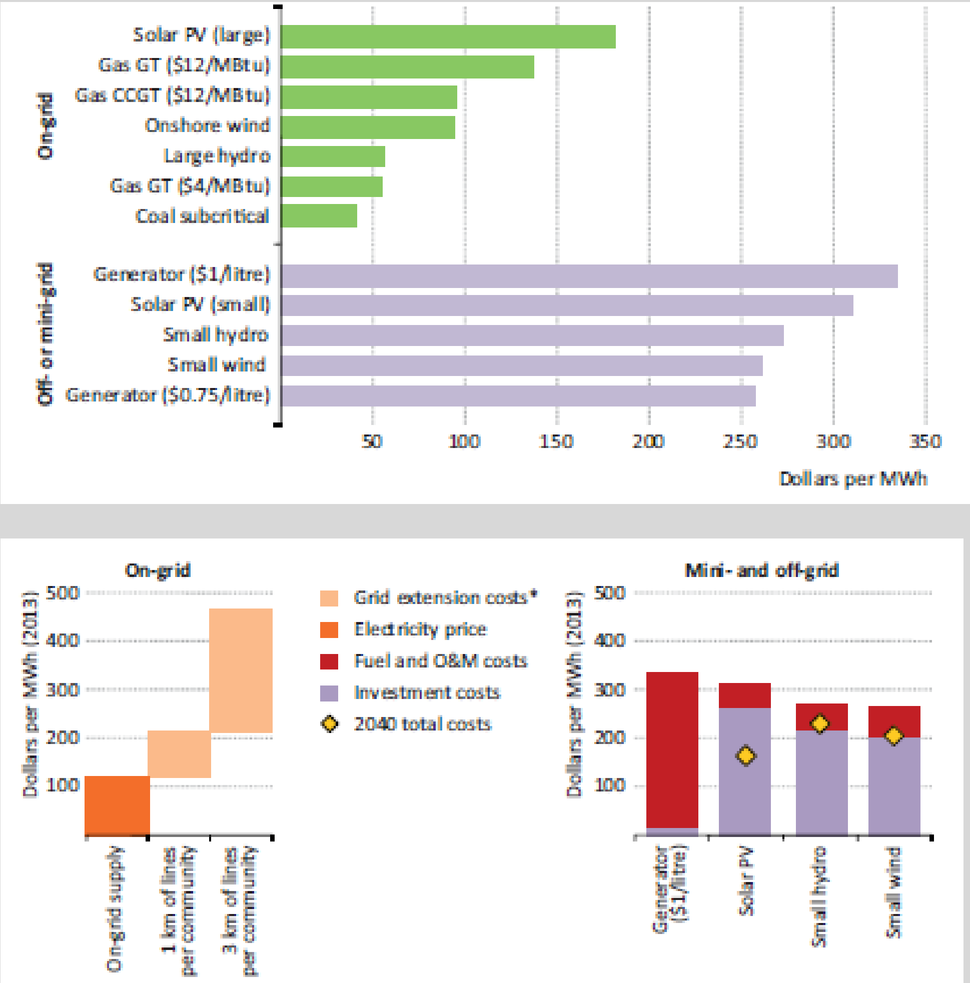
- Installation costs:
  - Grid extension: USD 22,000/km (for transmission line only)
  - Solar PV: USD 7,230/kWp
  - Generator costs: USD 13,200 (30KVA) and USD 6,000 (7KVA)
- A distribution grid of 2km at a fixed cost of US$18 000/km is assumed for each option (except in the case of SHS).
- 100 connections, each consuming an average of 50kWh/month is assumed for the grid extension (diesel)
- Cost of diesel: an additional 50% has been added to the diesel price to take account for transportation to site
- Discount rate: 10%

Rule of thumb grid extension cost:

- 5-100 connections/km (USD 580-4500 per connection).
- 3-5 connections/km (USD 4500-6500 per connection).
- < 3 connections/km (>USD 6500 per connection)
- The LCOE (levelised cost of energy) of hybrid-solar PV is generally competitive with that of grid extension when the extension would imply <10 connections/km
- IRENA (RE costs 2014): residential/SHS cost USD 0.14-0.47 per kWh (based on costs in selected countries)

Source: Norplan (2012). Policy Brief: Cost-benefit analysis of rural electrification

Figure 27 Levelised cost of electricity for on-grid and off-grid technologies in Sub-Saharan Africa (2012)



*Costs of grid extension are calculated as the average cost of extending the medium-voltage grid a certain distance (e.g. 1 km) to each community on a levelised cost basis.

Source: IEA (2014c), *Africa Energy Outlook*

The comparison between these two options turns on the density of settlement, with higher density favouring the development of mini-grids. The main technologies available for these types of systems are diesel generators or renewable energy technologies – solar photovoltaic (PV), small hydropower and small wind systems. The attractiveness of renewable technologies is much higher when costs are considered on a life-cycle basis, but finance must be available to meet the relatively high upfront outlay, which – even as costs come down – remains significantly above that required for a diesel generator. Generators have the advantage of providing power when needed (if fuel is available), but also face the significant downside of ongoing fuel costs, which can vary substantially. Diesel or gasoline is subsidised in some of the major oil-producing and exporting countries. Hybrid systems combining fossil fuel and renewables power generation (e.g. diesel and solar PV) can bring more flexibility and higher reliability of supply at acceptable costs.

Although, the 2007 ESMAP publication “Technical and Economic Assessment of Off-grid, Mini-grid and Grid Electrification Technologies” presents costs (for 2005; with projections for 2010 and 2015) in a systematic way. Although a bit dated, the publication gives the calculation methods and assumptions and, if needed, can be re-done with newer sets of data (see Annex A).

4. HEATING AND COOLING APPLICATIONS; FUELS

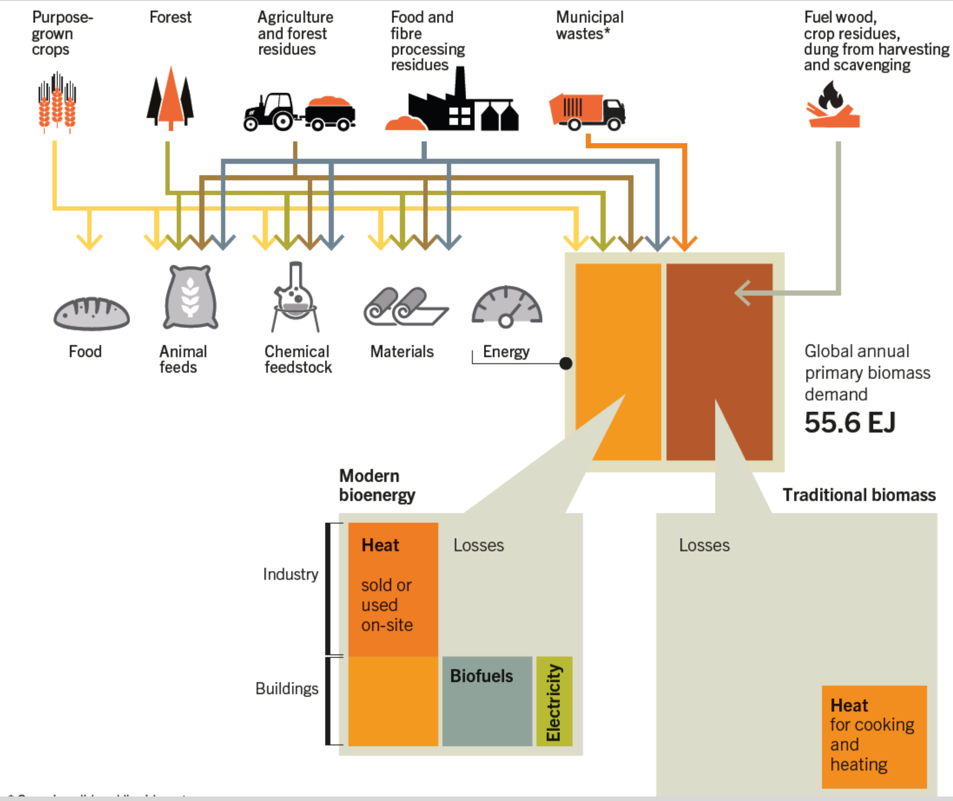
4.1 Heat applications (for productive and residential uses)

Energy use for heat accounted for about half of total world final energy consumption in 2015.Global consumption of heat energy grew at an average annual rate of less than 1% in recent years (REN21, 2016). Energy in thermal applications can be provided by burning fossil fuels (oil products, coal products, natural gas). Renewable energy is used to meet heating and cooling demands by means of solar thermal, geothermal, aerothermal or hydrothermal[2] as well as biomass resources in solid, liquid and gaseous forms. Bioenergy accounted for over 90% of modern renewable heat generation in 2015 (used in the industrial and buildings sector), solar thermal 8% (in the buildings sector mainly) and geothermal energy 2% (REN21, 2016).

4.2 Biomass heat and fuels

Bioenergy is energy derived from biomass (for cooking, heat, fuel, power) and can be classified in **traditional biomass** – fuelwood, charcoal, dung used in traditional devices (for cooking, heating, lighting) and **modern biomass** – used directly as above in modern devices and/or processed or converted into biofuels for heat, mechanical power and electricity. Approximately 60% of total biomass used for energy purposes is traditional biomass (REN21, 2016).

Figure 28 Global bioenergy demand (2014)

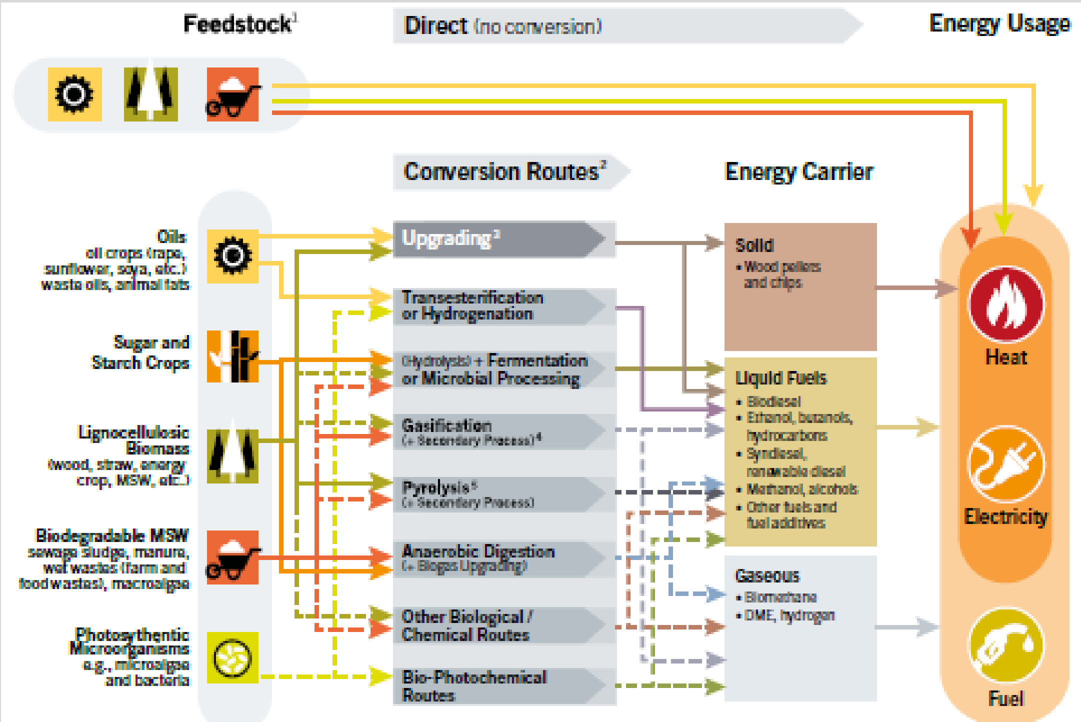


Source: REN21 (2014)

[2] Heat pumps utilise the ground, ambient air or water bodies for heating and cooling.

Box 2 Conversion and uses of biomass for energy

Biomass use for energy is multi-faceted: many different raw and/ or processed types of biomass can be transformed via numerous conversion technologies for use in energy sectors (residential, commercial, and industrial heating, electricity, or transport (figure taken from REN21, 2015, Fig. 6)



Globally, biomass was used to produce an estimated 12,500 TWh (45 EJ) of heat in 2014/15 and accounting for nearly 77% of total global primary bioenergy demand. Roughly 70% (8,805 TWh, 31 EJ) of this was generated from traditional biomass, which is used for heat primarily in Asia (5,305 TWh or 19.1 EJ) and Africa (3,222 TWh or 11.6 EJ; REN21, 2015, 2016). Biomass has many **alternative uses**, such as food and animal feeds, material (e.g. construction) and chemical products.

Biomass **feedstock** can be divided into the following categories:

- From natural resources (forest, grassland, woodland, aquatic biomass)
  - Naturally grown (wood and crops)
  - Agricultural, agroforestry and forestry schemes (crops, wood)
- Forest and agricultural by-products (such as sawdust, cereal brans)
- Organic content in waste streams (municipal waste, wastewater, industrial waste)
- Dedicated energy crops (different from natural resources crops in the sense that these are grown for energy purposes, sugar crops, starch crops, oil crops, lignocellulosic crops)
- Woody crops, oil crops and sugar/starch crops, aquatic feedstock (algae).

Solid biomass includes wood and wood residues (sawdust, bark) that has been used for thousands of years for cooking and heating, and as dry agricultural residues that can be used burnt directly (*direct combustion*) or converted into a solid, liquid or gaseous fuel with lower moisture content and better calorific value, by mechanical means (*pellets*, *briquettes*) and thermochemical means (charcoal production, gasification). The fuel obtained (*charcoal*, *wood/producer* gas) can be burnt in heat applications or power generation.

Wet residues (animal manure; wastewater; waste from food industry), MSW (municipal solid waste) as well as certain energy crops (e.g. elephant grass) can be used in bio-digesters to produce *biogas* in a process called anaerobic digestion. Another biochemical conversion method is the production of *ethanol*, usually from dedicated energy crops (sugar crops, such as sugar cane, or starch crops, such as maize) to be used as *transport fuel*. *Biodiesel* is produced from vegetable oil.

Worldwide, charcoal, fuel wood, crop residues are used predominantly for traditional heating and cooking. Similarly, Biogas is also produced in small, domestic-scale digesters, mainly in developing countries—including China, India, Nepal, and Rwanda—and is combusted directly to provide heat for cooking (REN21, 2014). Wood pellets and wood chips, as well as biodiesel and ethanol, all are now commonly traded internationally in large volumes

4.2.1 Modern bio-heat applications

Solid, liquid, and gaseous biomass fuels can be combusted to provide higher-temperature heat (200–400 ˚C) for use by *industry*, *in district heating schemes*, *in agricultural processes***,** and in combined heat and power *(CHP) plants*. They also can be combusted for use at lower-temperature heat (<100 ˚C) for cooking and water heating*;* drying; for heating water for domestic, commercial, or industrial use; and for heating space in individual buildings. Biomass is the most widely used renewable source for heating by far, accounting for approximately 90% of heat from modern renewables; solid biomass is the primary fuel source (REN21, 2014). Modern bioenergy applications provided some 14.4 EJ of heat in 2015, of which an estimated 8.4 EJ was for industrial uses and 6.3 EJ was consumed in the residential and commercial sectors, used principally for heating buildings and cooking (REN21, 2016). Most industrial-scale biogas production is in the United States and Europe, although other regions increasingly are deploying the technology as well

Table 17 Capital costs and LCOE of biomass for heating (hot water, steam), space heating and cooling

HOT WATER / HEATING / COOLING					
Technology	Plant size	Capacity factor	Conversion efficiency	Capital costs (USD/kW)	Typical energy costs (LCOE US cents/kWh)
Biomass heat plant	0.1–15 MW_{th}	~50–90%	80–90%	400–1,500	4.7–29
Wood pellet heater	5-100 kW_{th}	15-30%	80-95%	360-1,400	6.5-36
Biomass CHP[5]	0.5–100 kW_{th}	~60–80%	70–80% for heat and power	600–6,000	4.3–12.6

Source: TAF SE4All (2015-16), data taken from REN21 (2015)

TECHNOLOGY	TYPICAL CHARACTERISTICS	CAPITAL COSTS USD / kW	TYPICAL ENERGY C. LCOE – US cents / kWh
Heat Pump: Ground-source (residential and commercial)	Plant size: 10–350 KW_{th} Conversion efficiency: 280-500%	500–2,250	7–13
Heat Pump: Domestic water heaters	Plant size: 1–2 KW_{th} Conversion efficiency: 250–300%	300–350	6–7
Heat Pump: Water-source (residential, including multi-family)	Plant size: 4–40 KW_{th} Conversion efficiency: 300–400%	500–700	5–7
Heat Pump: Air-source	Plant size: 1–2 KW_{th} Conversion efficiency: 300–400%	350–400	5–7

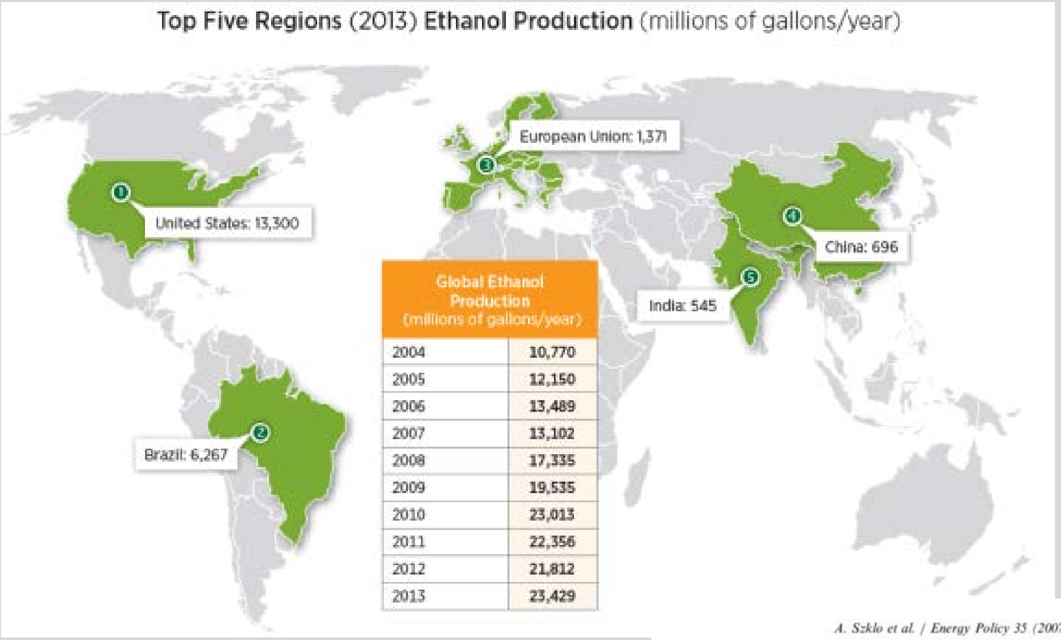
Source: REN21 (2015)

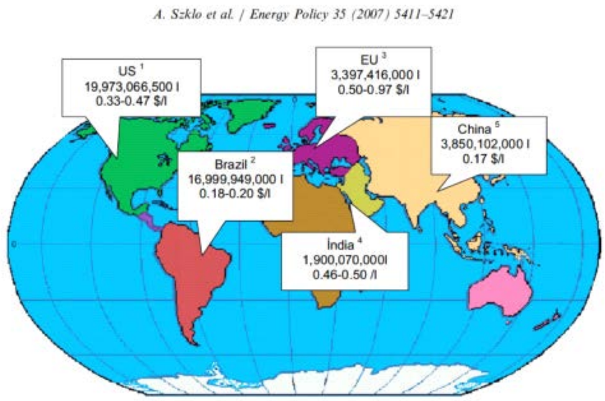
4.2.2 Liquid fuels

*Ethano*l is produced by fermentation of sugar crops (e.g. sugarcane) or starch crops (after converting starch into sugars, e.g. corn, wheat). The fluid obtained is distilled to get anhydrous (99-100%) or hydrous ethanol (95-96%); anhydrous ethanol can be blended with gasoline and hydrous ethanol as fuel for dedicated internal combustion engines. Production from sugarcane is often more cost-effective than from other crops, because By-product bagasse (30% of weight of plant) is used on-site to generate steam for CHP (for distillation and other heat uses) and electricity needs (sometimes excess is delivered to the grid). About 70-80 litres of ethanol per ton of sugarcane (about 6000 litres per hectare).

Straight vegetable oil (SVO) can be used to replace (partially) diesel fuel in diesel engine (for stationary applications); if used as single fuel, engine modification is needed. Transesterification of vegetable oil (using methanol and a catalyst) produces *biodiesel*. The characteristics are close to that of diesel and transesterification of vegetable oil (using methanol and a catalyst) and no engine modifications are required. Biodiesel and ethanol are practically the one available renewable transportation fuels.

Figure 29 Global production and costs of liquid biofuels





Sources: Above: www.cleantechnica.com
Below: REN21 (2014 and 2015), IISD, Biofuels at what cost? (2013)

Estimated production cost (USD per litre)
Soybean oil: 0.56-0.72 (Argentina); 1.00-1.20 (global) Palm oil: 1.00-1.30 (Indonesia, Malaysia) Rapeseed oil: 1.00-1.30 (EU)
Sugar cane: 0.82-0.93 (Brazil) Maize (dry mill): 0.85-1.28 (USA)

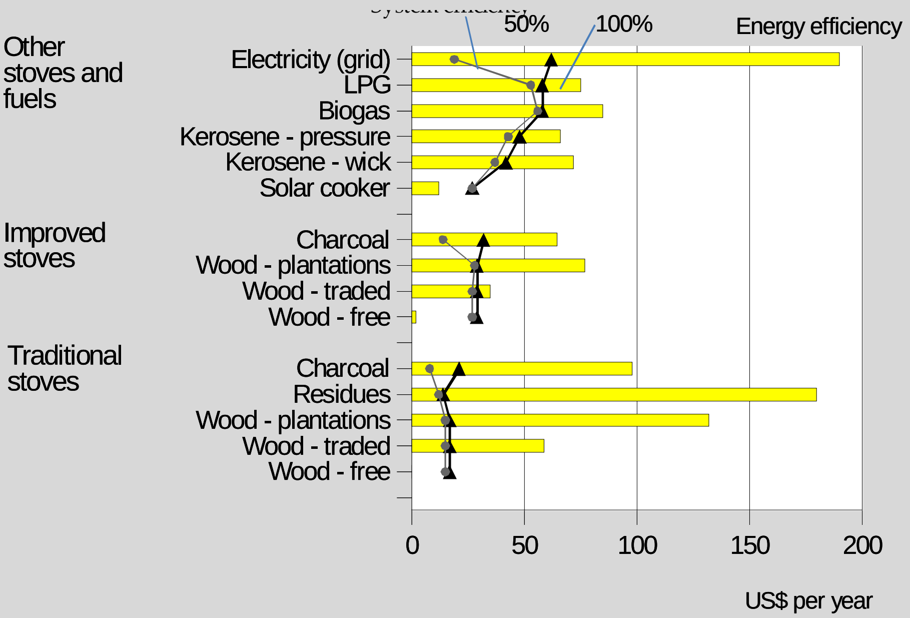
Average EU prices per litre (in EUR), 2011			
Ethanol	0.63	Biodiesel	0.90
Ethanol (adjusted for energy content)	0.85	Biodiesel (adjusted for energy content)	0.99
Gasoline	0.72	Diesel	0.77
Difference (adjusted for energy content)	0.13	Difference (adjusted for energy content)	0.22

4.2.3 Traditional uses of bioenergy and modern methods

Traditional' bioenergy, can be classified as:

- Systems in open stoves, ovens or fires or any system that releases indoor smoke
- Traditional methods of charcoal production (e.g. in earth mounds or pits)

Figure 30 Comparison of cost of cooking fuels



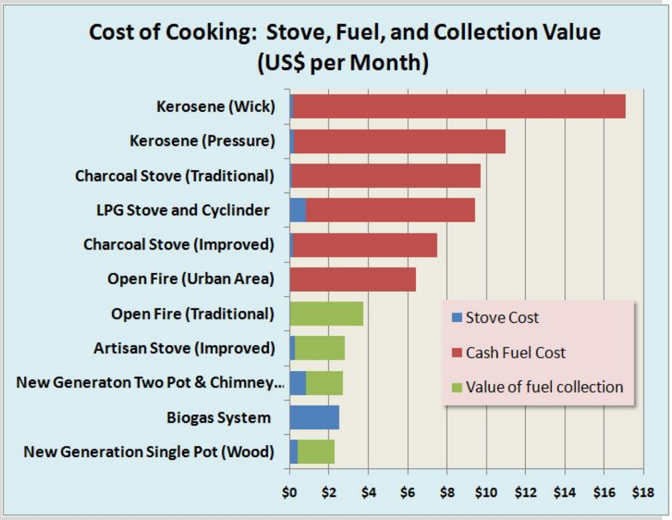
Open fire and traditional mud stoves have been reputed to have low efficiencies, varying between 5 and 15%. Simple improvements can yield a more efficient combustion. Firstly, heat loss can be reduced by enclosing the fire by constructing a stove. Adding a chimney to the stove, improves air draft and conduct exhaust gases outside the dwelling. With improved stoves, efficiencies of 15-45% (site-built oven), 20-30% (metal stove) up to 50% have been obtained. Charcoal is relatively smokeless and has better burning characteristics than wood. It has a higher net heating value than wood (29 and 16 MJ per kg), it is lighter an easier to handle and transport. In urban areas, it is often easier to buy. Charcoal stoves are made of metal and have an efficiency of 10 to 20%. Improved popular types include the Thai bucket stove and the Kenyan improved *jiko*, with efficiencies of 25-40%. However, because charcoal is made of wood, the efficiency of the charcoal production is as important as that of the charcoal stove itself. With traditional methods, it takes from 5 up to 12 tonnes of wood to produce 1 tonne or charcoal. Typically, cooking with charcoal consumes more than twice as much wood as burning firewood directly.

This indicates by "system efficiency" in the figure, i.e. the overall conversion efficiency is determined by multiplying 'stove efficiency' with the 'conversion efficiency' of production of the fuel.

Source: J. van den Akker

Another issue is the cost of fuel. Traditionally, wood is gathered and is free in terms of monetary costs. However, there is a 'value' involved in the sense that people have to spend time on wood collection, time which could be spent in more useful activities, as is indicated in the figure on the left

Source: www.energyfordevelopment.com



Consumption of fuelwood for traditional energy uses remained stable in 2015 compared to previous years, at an estimated 1.9 billion cubic metres (m3); the largest shares of fuelwood (as well as other fuels such as dung and agricultural residues) are consumed in Asia, South America and Africa (REN21, 2016). The use of charcoal for cooking in many developing countries reached an estimated 55 million tonnes in 2015.

Many people use wood or some form of biomass fuel; usually biomass fuels are easily accessible and biomass fuels are more affordable to the poor. Energy conversion efficiency of traditional stoves only 5-15%, while with *improved cooking stoves* (ICS) efficiencies of 20-60% can be obtained. As alternative, *fossil fuels* can be used. LPG cooks fast and efficient (8-9 times that of firewood and 2 times better than charcoal); often LPG is readily available in (semi-)urban areas. Kerosene stoves are also used (in simple wick stoves to pressurized stoves). Unlike LPG is can be bought in small quantities, but kerosene is highly flammable and can cause fires and deaths. Stoves have been developed that use *gellified ethanol* (gelfuel), about 55,000 have been introduced (mainly in Africa).

Biogas is used in rural areas in certain countries, notably China, India, Nepal and Vietnam. In 2014, China had an estimated 100,000 large-scale modern biogas plants and 42 million residential-scale bio-digesters (where the fuel is used primarily for cooking). India has about 4.75 million plants, Nepal 250,000 and Vietnam about 125,000 (REN21, 2016 and ENEA, 2013).

Table 18 Costs of biogas in small-scale applications

A typical rural family with 3-10 cattle (stationary) can produce 1-3 m^3 of gas to provide needs for cooking and lighting.

Biogas system by size of fermenter	3 m^3	12 m^3
Required number of cows (cross breed, zero grazing)	2-3	8-12
Manure feed (litres/day)	50	200
Water feed (litres/day)	25	100
Biogas production (m^3)	1	4
Daily cooking hours (using a two burner stove)	1.5-2	6-12
Slurry production (litres/day)	75	300

Costs quoted in literature of small biogas systems are highly variable. REN21 (2015) mentions USD 500-1000 per unit (with digester size of 6-8 m^3). The SNV publication "*Productive Biogas: Current and Future Development*" gives case studies of biogas applications in various countries, of which the financial and cost figures are summarised below:

	Vietnam	Uganda	Honduras	Mali	Peru
Feedstock	Pig manure	Water hyacinth Cow manure	Coffee wastewater	cattle dung and other	Horse and cow manure
Digester volume (m^3)	50-500	183	152	26	150
Generator capacity (kW)	n.a.	12	14	7.5	16
Feedstock needed (kg/d) Mixing ratio (feedstock:water)	 1:2 or 1:3	WH: 2000; CM: 750 1:1	0.12 m^3/d n.a.	180 kg fresh dung 1:1	160 1:6
Expected biogas (m^3/d) Expected energy (kWh/d)	0.034 m^3/kg/d 6*0.29*m^3 gas	52.5 68	45.4 12.6	6 5	18 84.8
Actual biogas (m3/d) Actual energy (kWh/d)		12.38 15.47	45.4 12.6	2.64 2.8	18 16
Installation cost (EUR)	30-45/m^3	36,600	-	2,444	84,000 (plus power system)
Operational cost feedstock price	- free	6,195 EUR 4.5/MT (CM) EUR 11/MT (WH)	250,000 -	- -	EUR 0.36/kWh -
Energy sales revenues	own use	EUR 2/MT (WH) EUR 8/MT (CM)	-	EUR 0.5-1/m^3	EUR 0.30-0.41/kWh
Payback period	7-10 years	depends	14	8.5	-

4.3 Solar thermal heat and cooling

The estimated total cumulative capacity of solar thermal collectors in operation worldwide by the end of 2013 reached 375 GW_{th}, corresponding to 535 million m^2 of collector area (IRENA, 2015; IEA-SHC, 2014). In 2013, the top six countries in terms of total installed capacity of glazed water collectors were China (260 GW_{th}), Germany and Turkey (both around 11 GW_{th}), Brazil and India (around 4 GW_{th}). In terms of the amount installed per capita, Cyprus, Austria, Israel, Barbados and Greece were the top five countries. An interesting market for future STS deployment are the island and island-nations (IEA-IRENA, 2015). For example, the Barbados Government has supported development of a local solar thermal systems (STS) industry since the early 1970s through tax exemptions, levies on electric water heaters, mandates for STS deployment in housing developments and incentives to manufacturers (e.g., tax breaks) and end-users (e.g., rebates at ~50% of system cost). The REN21 (2016) report mentions installed capacity of 435 GW_{th} (622 million m^2), providing approximately 357 TWh (1,285 PJ) of energy (heat), of which 309 GW_{th} in China (71% of the global market).

The average costs for small domestic **solar hot water solar systems** (including auxiliary heater) vary widely (USD 250-2,500/kW) between different countries (IEA, 2012). Collector and mounts account for 50% of capital costs while tubing and insulation account for 16% and the storage tank for around 11%. Other system components are the valves, sensors and gauges, heat exchangers and pumps (NREL, 2012). The wide STS cost range results from the variety of technology types[3], quality, material and labour costs. In some emerging economies, prices could be less than half of the costs indicated, if more materials and parts of the system were produced locally (IRENA-IEA, 2015a). Costs is also different between low-temperature systems (USD 45-60/m^2) and high-temperature systems (USD 160-400 m^2).

The capital costs of **solar cooling** technologies are dominated by the solar block (37%), followed by the thermal chiller (29%). Other cost components are installation (19%), storage (8%), and the heat rejection loop (7%). Total system costs (in 2011/14) are in the range of USD 4,350-5,550/kW, while capital costs are in the range of USD 425/m^2 or USD 1 915/kW for a 100-kW thermal chiller. However, the costs of the adsorption chiller are highly dependent upon the scale ranging from USD 1,560/kW for 20 kW cooling capacity to USD 3,600/ kW for 200 kW cooling capacity (IRENA-IEA, 2015b)

The costs of **solar heat for industrial process** heat strongly depend on process temperature level, demand continuity, project size and the level of solar radiation of the site. For conventional solar thermal systems (flat plate and evacuated tube collectors), investment system costs range between EUR 250–1,000/kW in Europe, and around EUR 200–300/kW in India, Turkey, South Africa and Mexico. The energy costs for feasible solar thermal systems range from EUR 0.025-0.08/kWh, and a European roadmap targets solar heat costs of eurocents EUR 0.03–0.06/kWh (ESTIF, 2014; IRENA-IEA, 2015b).

For **solar concentrated systems**, heating costs are in the range of eurocents EUR 0.06-0.09/kWh with a target of EUR 0.04-0.07/kWh for concentrating systems by 2020 (ESTIF, 2014; IRENA-IEA, 2015b). Concentrated systems include Parabolic Dish Collectors (developed and used in India) with costs ranging from USD 400–1,800/kW, Parabolic Trough Collectors with costs ranging from USD 600–2,000/kW, and Linear Fresnel collectors in the range of USD 1,200–1,800/ kW. As of 2011/12, there were about 200 CSH worldwide, of which about 85 in India. In India, number of CSH increased to about 250 in 2015; total collector area of about 48,000 m2. Investment cost: about USD 330/m2 with payback times of about 6 years[4].

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3 The solar collector is the key component of a solar thermal system. Two dominant designs exist: flat-plate solar collectors (FPC) and evacuated tube solar collectors (ETC). Globally, FPC account for around 26% and ETC for 65% of installed capacity. The other 8% of installed capacity are unglazed systems (often used to heat swimming pools; IEA-SHC, 2014). Regarding the system. a distinction can be made between thermo-syphon (or passive) systems and pumped (or active) systems.

4 Source: J. Van den Akker, Mid-term Review Report, UNDP/GEF project Solar Concentrators for Process Heat Applications in India (2014)

Table 19 Costs of solar thermal technology for residential applications

Costs	Typical current international values and ranges						
Typical Breakdown Heating (US)	Collector: 51% Storage: 11% BoS Costs: 38%						
Typical Breakdown Cooling (Greece)	Solar loop: 37%; Storage: 8%; Thermal chiller (100 kW): 29%; Heat rejection loop: 7%; Services: 18%						
System	Thermo-syphon direct					Thermo-syphon indirect	
Country/Region	Australia	China	India[b]	South Africa	Turkey	Southern Europe	US[c]
Investment costs[a], USD/kW	1100	100-250	130-180	630-650	130	630	2300
Collector yield, kWh/m²a	850	770-860	850	900-1000	770-900	685	550-700
Collector size, m²	3.5	4	2-4	2.5-4	4	2.5-4	6

Costs	Typical current international values and ranges				
System	Pumped Indirect			Pumped Direct	
Country/Region	US[c]	Central Europe	North Europe	US[c]	South Africa[d]
Investment costs[a], USD/kW	2300	850-1900	1600-2400	1700	760-820
Collector yield, kWh/m²a	550-700	395	360	550-700	900-1000
Collector size, m²	6	4-6	4-6	6	2.5-4

Application	Large Scale SWH	Solar CS[e]		SWH district heat	Solar Cooling
Country/Region	Europe	China	Germany	Denmark	Global
Investment costs[a], USD/kW	350-1040	980-1400	1800	350-400	1600-3200
Collector yield, kWh/m²a	685	580	530-622	450-480	395-685

Source: IRENA-IEA (2015), Table 2

Table 20 Costs of solar thermal technology for industrial processes

Solar concentrating technology:

	Specific thermal power (kW/m²)	Location	Cost (USD/m²)	Cost (USD/kW)
CPC vacuum tube	0.60-0.65	China	130	200-220
		Europe	450-900	690-1500
	0.3	India[a]	333	1133
Parabolic dish fixed	0.21-0.31	India	113-300	365-1430
Parabolic dish tracking	0.34-0.74	India[bc]	300-600	600-1760
Parabolic trough	0.50-0.56	Europe	650	1160-1300
	0.22- 0.28	India[d]	445	1580-2040
	0.55-0.7	Mexico	400-629	570-1100
Linear Fresnel	0.50-0.56	Europe	650-900	1160-1800

Source: IRENA-IEA (2015), Table 2

4.4 Solar water pumping

Solar-based irrigation solutions can be competitive on a life-cycle basis against pumps powered by fossil fuels, they are a capital-intensive technology with front-loaded investments that pay back over time. System costs continue to fall as a result of the dramatic reduction in solar photovoltaic costs, approximately 80% between 2012 and 2015 (IRENA, 2016b). A recent study by SNV (2014) compares conventional technologies (petrol and diesel pump sets), along with an inventory of RE alternatives: wind pumps, solar PV pumps, solar thermal pumps and biogas (see the Table below).

Table 21 Costs of small-holder irrigation

Plot size and water requirements		Unit	Remarks
Plot size	2 000	m²	Plot size under irrigation
Total water lifting	7,0	m	Based on water depth and possible water lifting
Required pump capacity	6,0	m³/day	Based on peak water need
Peak water need	6,0	mm/m²/day	Based on maximum evaporation
Peak water need	6,0	l/m²/day	
Average water need	3,0	l/m²/day	Used in calculations
Operating costs variables			**Based on:**
			http://chartsbin.com/view/5437
Petrol / gazoline costs	1,20	€/l	http://chartsbin.com/view/1115
Dielsel costs	1,00	€/l	http://chartsbin.com/view/1128
Biogas costs	0,00	€/m³	Cost of biogas unit not included

		petrol pump	diesel pump	biogas combution engine	solar PV Low end	Solar PV High end	Solar Thermal Sunflower	Windmill
Running costs								
Pump capacity	m³/hr	9	36	9	1,2	1,2	1,3	1,5
Punning hours	hr/day	0,7	0,2	0,7	5,0	5,0	4,6	4,0
Running costs	€/day	0,48	0,12	0,00	0,00	0,00	0,00	0,00
Running costs per season	€/season	58,56	14,23	0,00	0,00	0,00	0,00	0,00
Annual costs								
Maintenance costs	€/yr	39	77	99	97	201	42,25	45
Financing costs								
Life time	yr	4	7	15	15	15	8	15
Total investment costs	€	170	440	950	530	2815	310	900

Source: SNV (2014)

Another way to compare is to look at the years to breakeven, i.e. when will the lifecycle cost of the RE pump become lower than that of the diesel pump. The following table gives the example of an analysis in Namibia after how many years does a solar pump become cheaper than a diesel pump for different heads and daily water output.

Table 22 Years to breakeven over the operating life of PV and diesel pumps, Namibia

	Daily water [m³/day]								
Head [m]	3	4	6	8	13	17	25	33	50
20	0.0	0.0	0.0	0.0	0.2	0.5	1.0	1.3	2.6
40	0.0	0.0	0.2	0.5	0.8	1.2	2.6	2.8	5.6
60	0.0	0.1	0.5	1.0	1.2	2.6	3.5	5.9	7.2
80	0.0	0.3	1.0	1.7	1.8	3.6	6.4	6.7	7.8
120	0.0	0.9	1.9	2.7	4.1	7.1	8.2	Diesel	Diesel
160	0.2	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
200	0.6	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel

Source: EmCON (2006)

Box 3 Gujarat, India; solar PV pumps in salt production

Nearly 70% of India's salt is made in Little Rann of Kutch in Gujarat. The majority of the 43,000 salt pan farmers use inefficient diesel-powered water pumps to extract brine from the ground as part of the salt harvesting process. As a result, diesel accounts for a significant proportion of farmers' production costs. In fact, farmers spend up to 40% of their annual revenue of around EUR 1225 per season on buying diesel for the next production season, thus reducing disposable income.

Powering pumps with solar energy can reduce production costs, as well as increase reliability, efficiency and salt harvest outputs. A solar PV pump (2 kW array and 2 0.75 kW pumps) will cost EUR 2,153 (20 years lifetime and 5 years of the pump) in comparison with an equivalent diesel pump costing EUR 643 (about 7 years lifetime). However, depending on the use (about 16 hours per day in the salt extraction season of 180 days), using PV means avoiding the use of 1,440 litres of diesel and additional savings of about 603 per season. Thus, once the pump is repaid (in 3-4 years), the farmer will save 40% above their annual earning

Source: TAF SE4All (2015)

4.5 Solar desalination

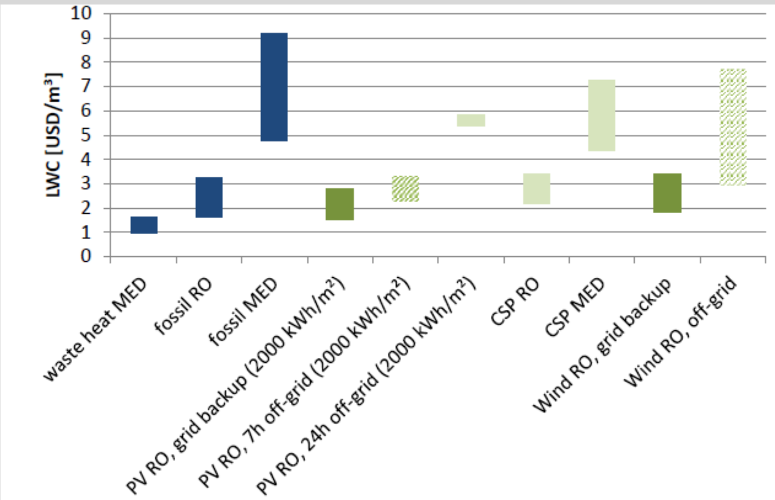
Today's global desalinated water production amounts to about 65.2 million m^3 per day (24 billion m^3 per year), equivalent to 0.6% of global water supply. Major desalination technology options are based on thermal processes using both heat and electricity, and membrane technologies using electricity only. The dominant technology is Reverse Osmosis (RO), which accounts for 60% of the global capacity, followed by Multi Stage Flash (MSF), with a 26.8% share. The larger desalination plants can reach a capacity of up to 800,000 m^3 per day or more.

Table 23 Comparative costs for renewable desalination

	Water cost (USD/m^3)
Solar stills (passive)	1.3-6.5
PV (reverse osmosis)	Brackish water: 6.5-9.1 Sea water: 11.7-15.6
PV (electro-dialysis)	Brackish: 10.4-11.7
Wind (reverse osmosis)	Brackish water: 3.9-6.5 Sea water: 6
Wind (electro-dialysis)	Brackish: 2.0-3.5
Geothermal	Sea water: 3.8-5.7

Source: IRENA-IEA (2013)

Figure 31 LCOE estimates for desalination technologies for islands



Source: IRENA (2015c). Shaded areas represent technologies in R&D stage.

The cost of desalination (with fossil fuels) has been decreasing over the last years down to USD 0.5/m^3, while market prices for desalinated water are typically between USD 1-2/m^3. Renewable energy can play an important role in desalination.

Renewable technologies that are suited to desalination include solar thermal, solar photovoltaics (PV), wind, and geothermal energy.

Table 24 2005 Conventional power technology capital cost (USD/kWh)

Technology	Life Years	Capacity Factor %	Rated Output kW	Engineering	Equipment & Materials	Civil	Erection	Process Contingency	Total
• Diesel/Gasoline Generator	10	30	0.300	–	890	–	–	–	890
	10	30	1	–	680	–	–	–	680
	20	80	100	10	600	10	20	–	640
Base Load	20	80	5,000	30	510	30	30	–	600
Peak Load	20	10	5,000	30	510	30	30	–	600
• Microturbines	20	80	150	10	830	10	20	90	960
• Fuel Cell	20	80	200	–	3,100	–	20	520	3,640
	20	80	5,000	–	3,095	5	10	520	3,630
• Oil/Gas Combustion Turb.	25	10	150,000	30	370	45	45	–	490
• Coal Steam (with FGD & SCR) SubCritical	30	80	300,000	100	870	110	110	–	1,190
SubCritical	30	80	500,000	90	850	100	100	–	1,140
SC	30	80	500,000	100	880	100	100	–	1,180
USC	30	80	500,000	110	850	100	100	100	1,260
• Coal IGCC (without FGD & SCR)	30	80	300,000	150	1,010	150	100	200	1,610
	30	80	500,000	140	940	140	100	180	1,500
• Coal AFBC (without FGD & SCR)	30	80	300,000	110	730	120	120	100	1,180
	30	80	500,000	110	680	120	110	100	1,120
• Oil Steam	30	80	300,000	80	600	100	100	–	880
Oil/Gas (comb. Cycle)	25	80	300,000	50	480	50	70	-	650

2005 Conventional power technology generating cost (USD/kWh)

Technology		Rated Output kW	Levelized Capital Cost	Fixed O&M Costs	Variable O&M Costs	Fuel Costs	Total
• Diesel/Gasoline Generator		0.300	5.01	–	5.00	54.62	64.63
		1	3.83	–	3.00	44.38	51.21
		100	0.98	2.00	3.00	14.04	20.02
	Baseload	5,000	0.91	1.00	2.50	4.84	9.25
	Peak Load	5,000	7.31	3.00	2.50	4.84	17.65
• Microturbines		150	1.46	1.00	2.50	26.86	31.82
• Fuel Cell		200	5.60	0.10	4.50	16.28	26.48
		5,000	5.59	0.10	4.50	4.18	14.36
• Combustion Turbines	Natural Gas Oil	150,000	5.66 5.66	0.30 0.30	1.00 1.00	6.12 15.81	13.08 22.77
• Combined Cycle	Natural Gas Oil	300,000	0.95 0.95	0.10 0.10	0.40 0.40	4.12 10.65	5.57 12.10
• Coal Steam (with FGD & SCR)	SubCritical	300,000	1.76	0.38	0.36	1.97	4.47
	SubCritical	500,000	1.67	0.38	0.36	1.92	4.33
	SC	500,000	1.73	0.38	0.36	1.83	4.29
	USC	500,000	1.84	0.38	0.36	1.70	4.29
• Coal IGCC (without FGD & SCR)		300,000	2.49	0.90	0.21	1.79	5.39
		500,000	2.29	0.90	0.21	1.73	5.14
• Coal AFBC (without FGD & SCR)		300,000	1.75	0.50	0.34	1.52	4.11
		500,000	1.64	0.50	0.34	1.49	3.97
• Oil Steam		300,000	1.27	0.35	0.30	5.32	7.24

Table 25 2005 Renewable power technology capital cost (USD/kW)

Technology		Life Years	Capacity Factor %	Rated Output kW	Engineering	Equipment & Materials	Civil	Erection	Process Contingency	Total
• Solar-PV		20	20	0.050	–	6,780	–	–	700	7,480
		20	20	0.300	–	6,780	–	–	700	7,480
		25	20	25	200	4,930	980	700	700	7,510
		25	20	5,000	200	4,640	980	560	680	7,060
• Wind		20	25	0.300	50	3,390	770	660	500	**5,370**
		20	25	100	50	2,050	260	160	260	2,780
		20	30	10,000	40	1,090	70	100	140	1,440
		20	30	100,000	40	940	60	80	120	1,240
• PV-wind-hybrid		20	25	0.300	30	4,930	460	390	630	6,440
		20	30	100	130	3,680	640	450	520	**5,420**
• Solar Thermal With Storage		30	50	30,000	920	1,920	400	1,150	460	**4,850**
Without Storage		30	20	30,000	550	890	200	600	240	2,480
• Geothermal	Binary	20	70	200	450	4,350	750	1,670	–	7,220
	Binary	30	90	20,000	310	1,560	200	2,030	–	4,100
	Flash	30	90	50,000	180	955	125	1,250	–	2,510
• Biomass Gasifier		20	80	100	70	2,490	120	70	130	2,880
		20	80	20,000	40	1,740	100	50	100	2,030
• Biomass Steam		20	80	50,000	90	1,290	170	70	80	1,700
• MSW/Landfill Gas		20	80	5,000	90	1,500	900	600	160	3,250
• Biogas		20	80	60	70	1,180	690	430	120	2,490
• Pico/Micro Hydro		5	30	0.300	–	1,560	–	–	–	1,560
		15	30	1	–	1,970	570	140	–	**2,680**
		30	30	100	190	1,400	810	200	–	2,600
• Mini-hydro		30	45	5,000	200	990	1,010	170	–	2,370
• Large-hydro		40	50	100,000	200	560	1,180	200	–	2,140
• Pumped Storage		40	10	150,000	300	810	1,760	300	–	3,170

Note: "–" means no cost needed.

Source: ESMAP (2007)

2005 Renewable power technology generating cost (USD/kWh)

Technology		Rated Output kW	Levelized Capital Cost	Fixed O&M Costs	Variable O&M Costs	Fuel Costs	Average Levelized Cost
• Solar-PV		0.050	45.59	3.00	13.00	–	61.59
		0.300	45.59	2.50	8.00	–	56.09
		25	42.93	1.50	7.00	–	51.43
		5,000	40.36	0.97	0.24	–	41.57
• Wind		0.300	26.18	3.49	4.90	–	34.57
		100	13.55	2.08	4.08	–	19.71
		10,000	5.85	0.66	0.26	–	6.71
		100,000	5.08	0.53	0.22	–	5.79
• PV-wind-hybrid		0.300	31.40	3.48	6.90	–	41.78
		100	22.02	2.07	6.40	–	30.49
• Solar-thermal	With Storage	30,000	10.68	1.82	0.45	–	12.95
	Without Storage	30,000	13.65	3.01	0.75	–	17.41
• Geothermal	Binary	200	12.57	2.00	1.00	–	15.57
	Binary	20,000	5.02	1.30	0.40	–	6.72
	Flash	50,000	3.07	0.90	0.30	–	4.27
• Biomass Gasifier		100	4.39	0.34	1.57	2.66	8.96
		20,000	3.09	0.25	1.18	2.50	7.02
• Biomass Steam		50,000	2.59	0.45	0.41	2.50	5.95
• MSW/Landfill Gas		5,000	4.95	0.11	0.43	1.00	6.49
• Biogas		60	3.79	0.34	1.54	1.10	6.77
• Pico/Micro-hydro		0.300	14.24	0.00	0.90	–	15.14
		1	12.19	0.00	0.54	–	12.73
		100	9.54	1.05	0.42	–	11.01
• Mini-hydro		5,000	5.86	0.74	0.35	–	6.95
• Large-hydro		100,000	4.56	0.50	0.32	–	5.38
• Pumped Storage		150,000	34.08	0.32	0.33	–	34.73

Note: "–" means no cost needed.

Source: ESMAP (2007)

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ASCENDIS

Advisory Services on Climate, Energy and Development Issues

ASCENDIS is an independent office, founded in 2004 by Ir. Jan VAN DEN AKKER, a technology management scientist with a Master's degree from Eindhoven University of Technology (Netherlands), who has been working for almost 25 years in the area of clean technology, energy efficiency, renewable energy, energy access and climate change.

The acronym ASCENDIS stands for 'advisory services on climate, energy and development issues'. ASCENDIS specializes in strategic and practical advice on sustainable energy, covering areas like energy policy and strategies, rural energy, renewable energy, energy efficiency, sustainable transportation, biofuels, financing for energy, public-private partnerships, climate change mitigation and adaptation and climate funding and financing. ASCENDIS. offers services in Africa, Europe neighbourhood, Asia & Pacific and Latin America & Caribbean from offices in Netherlands (and as needed in Lima, Peru), to international development agencies and their local partners.

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