A COMPARATIVE REVIEW OF RENEWABLE ENERGY

Yusuf K. Gülüt

Akademi Teknik Musavirlik Co. Ltd., Istanbul, Turkey
e-mail: yusuf.gulut@akademiconsulting.com

***Abstract* - The urgent need for sustainable, secure, and competitive energy is now globally acknowledged. In this report, a holistic approach to energy management is presented as a combination of the utilization of renewable energy resources together with the rational use of energy and energy efficiency measures. Five main forms of energy found in the nature are compared in view of their primary, secondary and renewable sources, and their utilization capability in fulfilling today's energy needs. Twelve different types of renewable energy harvesting technology alternatives are compared regarding twelve criteria ranging from environmental friendliness to project implementation time, plus five basic financial parameters. The analyses presented in this report indicate that biomass has a number of outstanding features among other renewable energy types. A brief coverage of biomass types, worldwide biomass availability, and biomass-to-energy conversion technologies are presented. The report concludes with a short listing of the business opportunities available in the renewable energy industry.**

Keywords - *renewable energy, energy pyramid, energy conversion, energy storage, biomass.*

1. Introduction

Today, energy has become one of the essential needs of human life, perhaps right after water and food. Unfortunately, water and food also need a lot of energy to be made available for consumption nowadays. Human communities which at one time could produce their own food in a sustainable and quite self-sufficient way now expect energy to be sent to them from long distances for even grinding their wheat and cooking their food. What has happened is an industrialization and urbanization which took place without the necessary infrastructure being developed first. But we may not have the right to condemn the pioneers of industrialization for not having a strategic approach, because we are not sure how strategic we are able to think and act today. In the past, humans fought over food and water. Now, the globe is torn by wars over energy. Until recently, readily available energy sources were consumed as if they were almost unlimited. Now, we think they are about to be depleted. Nevertheless, the world is finally after *sustainable, secure, and competitive energy*, as it is clearly stated in national and international strategic plans [1], [4].

It is estimated that, from 2007 to 2035, renewable delivered energy use in the industrial sector worldwide will increase by an average of 1.8 % per year, and the renewable share of total delivered energy use in the industrial sector will increase from 7.2 % in 2007 to 8.3 % in 2035, meaning a difference of 1.1 %. It is further estimated that, in the same period world renewable energy use for electricity generation will grow by an average of 3.0 % per year, and the renewable share of world electricity generation will increase from 18.6 % in 2007 to 22.7 % in 2035, meaning a difference of 4.1 % [2].

On the other hand, the Commission of the European Communities states that "... Europe continues to waste at least 20% of its energy due to inefficiency"[3], and that "Although Europe is already one of the world's most energy efficient regions, it can go much further. In its 2005 Green Paper on Energy Efficiency, the Commission showed that up to 20% of EU energy use could be saved: equivalent to spending as much as € 60 billion less on energy, as well as making a major contribution to energy security and creating up to a million new jobs in the sectors directly concerned." [4]. Furthermore, the 2006 Spring European Council called for the adoption as a matter of urgency of an ambitious and realistic Action Plan for Energy Efficiency, bearing in mind the EU energy saving potential of over 20% by 2020 [3].

It can be deduced from the above data that projected energy gains from the efficient use of energy could be more than the projected contribution of renewable sources. Based on the above quoted statement that "Europe is already one of the world's most energy efficient regions", we might conclude that better efficiencies could be achievable and even higher energy gains be possible in other parts of the world.

In this report, we distinguish between **energy efficiency** achievable through *technology* measures and **rational use of energy** achievable through *behavioral* measures. Both of them together could be called "energy conservation".

In the Commission of the European Communities report entitled "An Energy Policy for Europe", the programme of energy efficiency measures at Community, national, local and international level are stated as [5]:

"• Accelerating the use of fuel efficient vehicles for transport, making better use of public transport; and ensuring that the true costs of transport are faced by consumers;
• Tougher standards and better labeling on appliances;

- Rapidly improving the energy performance of the EU's existing buildings and taking the lead to make very low energy houses the norm for new buildings;
- Coherent use of taxation to achieve more efficient use of energy;
- Improving the efficiency of heat and electricity generation, transmission and distribution;
- A new international agreement on energy efficiency to promote a common effort.**”**

We observe that the above list combines both energy efficiency and rational use of energy measures.

A holistic approach to solving the energy problem should include not only utilization of renewable energy but also measures for rational use of energy and energy efficiency because:

- Energy conservation through the rational use of energy and energy efficiency has the potential to provide energy gains of more than that achievable from renewable sources with the technology level projected to 2035, as shown in the above paragraphs.
- Whether derived from non-renewable or renewable sources, wasting of energy either through irrational use or inefficient utilization will require more resources of either type. Non-renewable resources are about to be depleted, and renewable ones are not yet deployable by the needed amounts.

This holistic approach can be illustrated by the “energy pyramid”[6], [7]. Figure 1 on the right shows an energy pyramid adapted for this report. Its shape reminds the fact that a pyramid should not be attempted to be constructed starting with its peak. One first needs to built its base, namely the layer of rational use. The second layer is the layer of energy efficiency. The third layer of renewable energy forms the peak. The rational use of energy has a higher priority than the energy efficiency because it has the potential for higher energy gains. Application of all the layers must of course be preceded by an analysis of the current situation, determination of what it should be, and synthesis of a solution, namely how the gap between the present and desired states shall be closed.

Table 1 on the right is a brief listing of energy consumption modalities. All the layers on the energy pyramid would be applicable to all of the existing modalities briefly listed in this table, and also those anticipated in the foreseeable future.

2. Rational Use of Energy

We define the ***rational use of energy*** as the optimal consumption of any kind of energy source while satisfying the minimum requirements of the purpose for which energy is consumed.

Rational use of energy requires a conscientious consideration and questioning of whether to consume energy or not, and if it is necessary, in what way, so as to consume the minimum amount. As such, rational use of energy is based on behavioral measures.

For this purpose, the following principles might be considered:

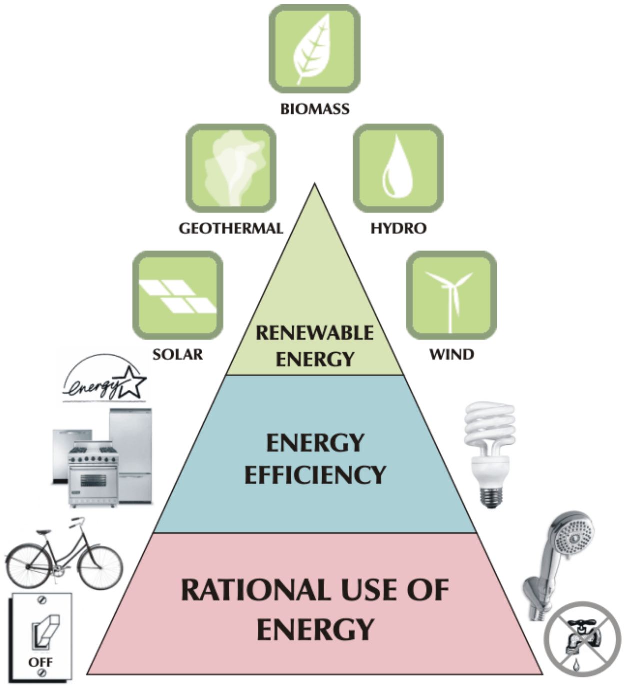

Figure 1. The energy pyramid. Rational use of energy is like the base of a pyramid, and it needs to be established first. Energy efficiency is the second floor, and renewable energy is the top of the pyramid. Adapted after modifications from [6] and [7]. Renewable energy icons adapted after modifications from [28].

Table 1. A brief listing of energy consumption modalities in which all the layers of the energy pyramid would be applicable.

- Space heating
- Space cooling
- Water heating & cooling
- Lighting
- Transportation
- Process heating
- Process cooling
- Electrochemistry
- Mobile mechanical drives
  - Agricultural
  - Commercial
  - Industrial
- Stationary mechanical drives
  - Pumping
  - Manufacturing
- Synthetic fuel production
- Conversion to electrical energy for further consumption in any of the above modalities

- The perceived need for a consumption of energy must be analyzed in view of serving a ***higher purpose***. In case the higher purpose could be satisfied by alternative means without consuming any energy or a lesser amount, this option should be chosen. For example, a car shall be driven to a nearby shopping area. The higher purpose is to buy groceries. If this purpose can be realized by walking down to the store and the grocery bags could be carried home, this option could be chosen because it would not consume any fuel.

- The effectiveness (efficacy) and efficiency of the alternatives in satisfying the higher purpose should further be analyzed and the optimal alternative should be selected. For example, going to the grocery store could be by a car, by a motorcycle, by a bicycle, or by walking. In case we need to buy a few small items, riding a bicycle would be time-wise more efficient than walking if there is a biking lane on the way. If we would be buying a lot of groceries, we may end up not been able to carry what we have purchased; so the walking or riding a bicycle may not be effective in serving the purpose. Next alternative is riding a motorcycle. If this option is not viable for some reason, now we need to take a car there. We can still do optimization in terms of higher (shopping) efficiency though! We can organize our visit to the store by the car so that neighbors could join us, or drop someone to somewhere on the way.
- The same amount energy consumed at different times of the day or different days of the week not only has different costs to the consumer, but also different costs to the energy providers. Multi-tariff billing of the consumer based on differing demand periods is well established in many countries. Another well established fact is that, the higher the peak demand, the higher the costs of investment and cost of operation of power plants in any country. Therefore the rational use of energy requires that we plan and organize for energy consumption during low demand periods.
- Life time energy cost, or "energy balance" should be considered with a strategic approach in the research, development, and production phase of goods or services. Consumers should be well informed about product alternatives offering lower lifetime energy cost, such as rechargeable batteries instead of disposable types [44].
- At the global, country, commercial, and household levels, the above principles of the rational use of energy could and should be applied for all of the energy consumption modalities briefly listed in Table 1 above.

In the above definition of the rational use of energy, energy conservation is achieved through behavioral measures. For example, a decision shall be made between driving a car and a bicycle. Once the option of driving a car is selected, how little fuel would be consumed per distance traveled will depend on the following factors:

- Proper maintenance of the car by its owner so that it consumes no more than the amount of fuel its manufacturer designed for.
- Selection and purchasing of a car with a small fuel consumption.
- Design and production of the car by its manufacturer so that it consumes the smallest possible amount of fuel per distance traveled.

The first two actions are behavioral measures on the owner, and we classify them as the rational use of energy consuming equipment.

The third one is a technological requirement on the manufacturer since it takes research and development; we therefore distinguish it from the rational use and classify it as an energy efficiency measure which we will treat in the next section. Because the rational use of energy is achievable through behavioral measures, education and training are the most important tools in this regard.

Table 2 below is a partial listing of behavioral measures for the rational use of electrical energy.

Table 2. A partial listing of behavioral measures for the rational use of electrical energy

- Completely turn off equipment which has a sleep mode power-off.
- Make use of occupancy sensors to turn off unneeded lighting.
- Make use of timers to turn equipment on and off automatically.
- Make use of ventilation whenever effective in place of air conditioning.
- Properly maintain all energy consuming equipment and promptly repair any equipment with an energy wasting defect.
- Turn off water heaters when not needed for an extended duration.
- During the acquisition of any energy consuming equipment, vehicles, etc., choose the one which consumes the minimum amount of energy for a given function.

3. Energy Efficiency

Efficiency is a measure of the output obtained from a process per unit input. In this report, we define ***energy efficiency*** actions as those actions directed towards maximizing the energy output per unit energy input, in the process of converting from one form of energy into other form or forms. The energy input and output of a conversion system could be expressed in power units such as kW, or energy units such as kWh. In this case the efficiency figure would be dimensionless, and it would usually be expressed in percentage. Sometimes, the output could be expressed in a unit representing some other useful work, such as distance traveled by a car, and the input the amount of fuel consumed. In this case the efficiency would be expressed as miles per gallon or liters per 100 kilometers.

A brief listing of energy efficiency actions technoand technology development examples in various fields is presented in Table 3 on the next page.

A number of important concepts which must be well comprehended when evaluating or comparing energy generating technologies and power plants are described in the Boxes 1 though 3 on the next page. These are:

- Power efficiency and energy harvesting efficiency.
- Availability factor and reliability factor.
- Capacity factor and load factor.

Box 1. Power Efficiency and Energy Harvesting Efficiency

In evaluating the efficiency of energy conversion systems, it is important to differentiate between what we will call **"power efficiency"** and **"energy harvesting efficiency"** of systems.

For example, the efficiency of photovoltaic (solar) cells are commonly stated in terms of electrical power output (kW) per solar power input (kW). A 14% efficiency stated for a solar panel of one square meter area means that at noon time with a solar irradiance of 1 kW/m2 (one sun), it will harvest 140 W of power. This is what we call the *power efficiency* for a solar cell. We may tend to treat different solar cells with the same power efficiency equally. But how much energy different solar panels with the same power efficiency could harvest in one day might be different. This is because the power efficiency of solar cells is not constant with changing irradiance. At 0.1 sun, the power efficiency of a silicon crystalline solar cell decreases by about 13%, while it increases by about 30% for amorphous triple cells [15]. Since the irradiance during a day varies between zero and one sun, the second type of solar cell will have a better performance in harvesting energy during a day. When two systems having the *same power output at one sun* are compared, the amorphous triple system will actually provide higher energy output in a day than the silicon crystalline system and therefore would have a higher *energy harvesting efficiency*, even though it has a lower power efficiency at one sun (~5%) as compared to the other (~14%).

It should also be noted that, insolation maps provided by many sources typically show the total incident solar energy resource (input) available to a fixed position flat plate collector, such as a photovoltaic panel, in terms of kWh/m2 per day, month, or year. The panel is assumed to be oriented and fixed towards south at an angle from horizontal equal to the latitude of the collector location. Some sources will also provide insolation maps which represent the resource available to concentrating systems that track the sun throughout the day [16]. Obviously, a solar collector tracking the sun will harvest a higher amount of energy in a given period than a fixed flat collector. Therefore, appropriate maps should be utilized for the application at hand. However, it should always be kept in mind that, both type of maps provide only the solar resource (input) available, but not the electrical energy convertible by a given type of solar system. Multiplying the resource available by the power efficiency of a solar system will give only an approximate value for the energy harvestable, as explained above. Similarly, wind turbines will differ in their ability to harvest wind energy at wind speeds lower than their rated value. Therefore, their energy harvesting efficiency would be different even if they have the same rated power for a given rotor diameter.

Since the cost of energy provided by a system mainly depends on how much energy it can harvest in its life time period, energy harvesting efficiency should carefully be considered in the feasibility studies of all energy conversion systems.

Box 2. Availability Factor and Reliability Factor

Availability factor of a power plant is the amount of time that it is ready and able (available) to generate energy over a certain time period divided by the same period, including planned maintenance down-time. **Reliability factor** is calculated similarly, but excludes planned maintenance down-time. Modern power plants may have reliability factors close to 99% and availability factors reaching 98% for wind turbines and 95% for gas turbines, [40], [41], [42].

Table 3. A brief listing of energy efficiency actions and technology development examples in various fields.

Energy Efficiency Actions	Technology Development Examples
Increasing the efficiency of energy consuming equipment	• Compact fluorescent and LED lamps • High efficiency electric motors • Hybrid cars
Increasing the efficiency of energy generation equipment	• Higher efficiency solar cells • Stirling engine • Permanent magnet alternators
Increasing the efficiency of electrical power handling equipment	• Higher efficiency transformers • Higher efficiency transmission and distribution systems • Higher efficiency AC/DC/AC converters
Recovery of waste heat	• Co- and tri-generation • Organic rankine cycle systems • Thermoelectric generator • Thermoacoustic heat transformer
Active harvesting of heat or cold from the environment	• Heat pumps • Phase change thermal storage materials
Increasing the efficiency of heat transfer	• Heat pipes
Prevention of heat loss or gain	• Vacuum insulated panel
General	• Energy Star Certification • TCO Certification

Box 3. Capacity Factor and Load Factor

Capacity factor is the ratio of energy a power plant has actually generated over a time period to the energy calculated by multiplying its nameplate (installed) power rating by the same time period. A capacity factor less than one (100%) could come out due to a plant being down for sometime due to corrective or preventive maintenance, unavailability of input source such as sun or wind, or because its operator chooses not to run it for any reason. A low capacity factor due to any cause increases the cost of energy a power plant generates because a bigger power plant is need to provide a given amount of energy. See Figure 2 for typical capacity factors achievable by various types of renewable power generating technologies where the highest and lowest values are 90% for geothermal and 21.7% for solar PV.

Load factor is the ratio of energy a power plant has actually generated over a time period to the energy calculated by multiplying the maximum power it ever generated by the same time period. When the capacity factor for a power plant is significantly lower than its load factor, it means that the installed capacity has been selected too large either for the input source, or the market demand [39].

Both capacity factor and load factor should carefully be considered in the financial feasibility studies of all energy conversion systems.

4. Main Forms of Energy

We cannot define the concept of energy itself [43], but we all feel that whatever we can comprehend in this world are *change*s, changes in the state of what are around us, and physics, biology, thermodynamics all tell us that no change is possible unless there happens a more fundamental change, actually an *exchange* of "energy" from one form to another. Perhaps we distinguish different forms of "energy" by the help of their different manifestations or their effects on our five senses. So, we concentrate on the *forms of energy*, and *conversion of energy from one form to the other.*

Table 4, placed at the end of the report is a comparison of the *main forms of energy* found in the nature, namely the chemical, electrical, light (electromagnetic), mechanical, nuclear and thermal energy in terms of following criteria:

- Primary sources and typical exploitable power levels per energy conversion plant.
- Derived (secondary) sources.
- Capacity factor of the primary Source.
- Available energy storage mediums.
- Available energy storage scale and storage duration.
- Single-step conversion technologies to other forms of energy.
- Conversion technologies and efficiency of conversion to electrical energy.
- Large-scale long-distance transmission capability.
- Transportation power capability.
- Large-scale universal utilization capability.

In this table it is interesting to note that, for every form of energy found in the nature there is a renewable source, except the nuclear energy, as shown in the second column.

In this table, we have evaluated the main forms of energy in terms of a concept we called "large-scale universal utilization capability" and defined as the qualitative aggregate of their following capabilities:

- Large scale and long duration storage capability
- Overall efficiency for being converted to other forms of energy
- Large-scale and long-range transmission capability
- Transportation power (fuel) capability.

Within the limitations of this approach, the large-scale universal utilization capability of *chemical energy* came out as *high*, which may explain the global contention over petroleum, and the same capability of *electrical energy* very high, which may explain why in the renewable energy literature "conversion to energy" usually means conversion to electricity. Among other energy forms, nuclear energy fared "low, together with risks", mechanical energy "little", thermal energy and light (electromagnetic) energy "very little" according to our evaluation.

Presently known primary sources of electrical energy in the nature is limited to lightning with only a few kWh energy per flash [56], [57], and electric fish which may generate a few watts [58]. The very high capability of electrical energy for large scale universal utilization is based on its secondary sources derived from other primary forms of energy available in the nature.

It should be noted that, light (electromagnetic) energy, which is available on earth as solar radiation in colossal amounts as compared to any other type of energy, is utilizable only locally. In its original form of light energy, solar energy has a low capacity factor, cannot be stored and transmitted in any significant amount, and does not have a significant transportation power capability. Therefore, we have rated its large-scale universal utilization capability as "very little".

5. An Evaluation of the Energy Needs of the Mankind

Mankind has utilized what is now called renewable energy since pre-historic times. For long spans of civilizations, all of the energy utilized by mankind came from biomass, wind, water, and biomechanical sources which are all renewable, except a limited amount from coal. Then, coal mining became widespread, petroleum exploitation started, and natural gas followed. For a while, humanity consumed these nonrenewable sources without much consideration of their depletion and the resultant environmental damages. Moreover, mankind literally got addicted to consuming these sources in a variety of ways, irrespective of the fact that they may not be abundant in their homeland, but nevertheless could be acquired in good quantities from other lands --nearby or far away, at costs that burden even the richest economies. Even worse, mankind got into a fierce contention for acquiring these non-renewable energy sources.

Now, mankind thinks that the non-renewable energy sources are really about to be depleted. Now, mankind thinks that all this consumption is not only destroying the environment in their homeland, but could be taking the whole globe to some grave destination called global warming.

Finally, the world appears to be after ***sustainable***, ***secure****, and* ***competitive*** *energy*, as stated in national and international policies [1].

In order to be ***sustainable***, an energy source must meet the following criteria, as adapted from [18]:

- Do not deplete natural resources;
- Have minimal or no negative environmental or social impact;
- Meet the needs of people today and in the future in an accessible, equitable and efficient manner;
- Have little or no net carbon or other greenhouse gas emissions; and
- Be safe today and not burden future generations with unnecessary risk.

In order to be ***secure***, an energy source must have the following virtues, as adapted from [18] and [19]:

- Be available close to points of use, so that it does not need to be procured from other national or international possessors.
- Be available worldwide, so that it will not be a source of greed and contention among nations; and
- Have little or no net greenhouse gas emissions, and

other locally or globally harmful environmental effects, so that it will not be subject to national or international sanctions.

In order to be ***competitive***, an energy source must meet the following criteria as adapted from [19]:

- Investment cost for its harvesting plant be compatible with the economy of the project owners/developers;
- Cost per unit of energy be within the reach of its consumers, preferably without subsidies;
- Be available close to points of use, so that part of it is not wasted in transmission, or that its transport is not costly;
- Have significant contribution to the local economy during its harvesting; and
- Generate new local jobs needed for its harvesting.

In this report, we recognize a fourth virtue for energy sources and call it ***dependability***. In order to be ***dependable***, an energy source must satisfy the following criteria:

- Have local alternatives to depend on in case its availability is reduced due to predictable or unpredictable reasons;
- The technology for harvesting it is already capable and reliable enough;
- There are new and promising harvesting technologies in the national and international research and development pipelines.

Mankind has actually been bestowed upon with a variety of energy sources some of which satisfy most of the above criteria to a large extend! And, these are nothing but what we now call renewable energy sources, namely biomass, geothermal, hydro, solar, tidal, wave, wind, and others.

6. Renewable Energy Types

A proper definition of renewable energy (one which includes all what it is, and excludes all what it is not) is not easily found in the literature. The National Renewable Energy Laboratory of the US department of Energy states that "there is no formal definition for this term. Typical usage defines it as any energy source that is replenished at least as fast as it is used. Standard examples are solar, wind, hydroelectric, and biomass products."[8]. Commission of the European Communities states that "'renewable energy sources' shall mean renewable non-fossil energy sources (wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases)" [31].

In this report we will adopt the first definition, and ***call renewable energy as any energy source that is replenished at least as fast as it is used.*** Table 5 on the right is a listing of most commonly utilized renewable energy sources, together with the *form of energy* they originally provide.

There are other types of renewable energy sources not included in Table 5 mainly because either technology for harvesting them is not yet mature, requires big investments, or only few sites in the world are suitable. Some of these are ocean thermal, ocean current, and ocean salinity gradient energy sources [20].

Table 5. A listing of most commonly utilized renewable energy sources, together with the *form of energy* they originally provide.

Biomass	Chemical Energy
Geothermal	Thermal Energy
Hydro	Mechanical Energy
Solar	Light (Electromagnetic) Energy
Tidal	Mechanical Energy
Wave	Mechanical Energy
Wind	Mechanical Energy

We should note that, the geothermal energy is not truly renewable, but it is perhaps practically inexhaustible within the time frame that humanity could ever need it. Nevertheless, we can fit geothermal energy into our definition of the renewable energy by limiting our project boundary to the volume of the rock from which we extract heat energy, and saying that the heat lost is replenished as fast as it is used by the vast neighboring hot regions of the earth, which themselves will not practically cool down. Fusion could also be considered as a practically inexhaustible source of energy, but it is commonly not included in lists of renewable energies perhaps because it is not yet fully realized.

Below we will treat in more detail each of the renewable energy sources. But we would like to immediately distinguish *biomass* among others for its virtue which is not shared by other renewable energy sources:

Except "energy crops", all of the biomass sources are waste products. With the technology available today, their utilization as a source of energy not only contributes to the energy needs of humanity, but also helps to eliminate waste or minimize the unwanted impacts of waste on the environment.

However their current limited application and low power levels are, energy generated by living creatures during their life activities can partly be tapped for good utilization. Every moment we are, for a multitude of purposes, making use of more than one type of "renewable energy" our own body generates. When we use a hand-crank flashlight, we are converting the mechanical energy coming from our body to electricity. That we will call *biomechanical energy*. When we warm the cold hands of our child coming from cold outside by our warm hands, we are supplying him heat energy. And that we will call *biothermal energy*. In the past humankind harnessed the renewable biomechanical energy offered by a surprisingly varied group of domesticated animals. Each animal was good for a certain mechanical drive need, and they still are. We now think that using a horse for going to the grocery store would not be effective, efficient, and economical. We are right. But who knows what we would think in some distant (maybe near?) future!..

So, Table 6 on the next page presents a brief listing of energy sources very renewably generated by living creatures, in order of estimated power levels.

Table 6. A listing of renewable energy sources generated by living creatures, in order of estimated utilizable power levels.

Energy Type and Estimated Power Levels	Example Utilization or Manifestation in Nature
Biochemical MW	• Biomass
Biomechanical kW	• Horse or dog powering a carriage • Horse pulling out water from a well
Biothermal mW~W	• Father warming the cold hands of his son by his warm hands
Bioelectrical mW~W	• Electric fish shocking a diver [58]
Bioluminescent µW~mW	• Click beetle, firefly, railroad worm, hatchetfish, jellyfish [59]

7. A Comparison of the Renewable Energy Types

In Table 7 placed at the end of the report, we have presented a comparison of a number of renewable energy sources and harvesting technology alternatives regarding their overall present and potential capability in providing mankind ***sustainable, secure, competitive, and dependable energy.*** In order to keep the comparison manageable in this report, a limited number of 12 selected criteria are treated in this table:

- Environmental friendliness (minimum harm)
- Positive contribution to the environment
- Worldwide availability
- Availability close to points of use
- Plant size scalability
- Current technological capability
- Potential for technology improvement
- Capacity factor
- Unpredictable source variability
- Land area occupation
- Implementation technology level
- Project implementation time

Each of the comparison criteria utilized in this table would be relevant with varying degrees for different levels or platforms for which renewable energy types are evaluated. We have considered four levels, namely:

- Global
- National
- Commercial
- Household

For example, while environmental friendliness is very relevant at the global level, its relevance at the national, commercial, and household levels may be perceived progressively less than what it deserves. In other words, some governments, some companies, or some households may not consider environmental sustainability very important in their evaluation of different energy types. On the other hand, “availability close to points of use”, and “land area occupation” criteria would be more relevant at the national, commercial, and household levels than at the global level. Therefore, different renewable energy types should be evaluated and compared in different tables for each four levels. However, in this report we have chosen to present a simplified comparison based on a combined evaluation of each criterion for all the levels.

Based on data collated and deduced from various references, a grade out of 5 was assigned to each of the 12 comparison criteria based on a combined evaluation of all the levels. Data sources and reasoning used in the assignment of the grades are presented in Appendix A.

A summary of this comparison is presented in Table 8 below.

Table 8. The result of a comparison made among main types of renewable energy for providing mankind sustainable, secure, competitive, and dependable energy (See Table 7 placed at the end of the report for details)

	Renewable Energy Type	Total Grade out of 100
1	Biomass, Small Scale	82
2	Biomass, Large Scale	73
3	Solar, Photovoltaic (PV)	70
4	Solar, Concentrated PV	63
5	Wind	58
6	Solar, Thermal Electric	57
7	Hydro, small scale, run-of-the-river	50
8	Enhanced Geothermal	48
9	Hydro-Geothermal	48
10	Hydro, large scale with dam	45
11	Tidal	37
12	Wave	35

Within the limitations of the selected criteria and the values assigned to them by the author, the above table indicates that small scale biomass has the highest total grade of 82/100 on a combined evaluation of global, national, commercial and household levels. Large scale biomass is the second, followed by photovoltaic solar and concentrated photovoltaic solar. Then, wind, thermal-electric solar, and small scale hydro follows. The rest of the energy types have received grades less than 50 out of 100.

It should be kept in mind that, when the evaluation is made for only one level such as household, different results shall be obtained.

The capital investment cost of various renewable energy plants, their operational costs, the cost of generating electrical energy per kWh and its selling price, the internal rate of return, and other financial criteria are additional important factors in evaluating renewable energy types. However, we have not included them in Table 7 because the relative weight of financial criteria could be very different than those treated in this table.

Financial data reported in the literature for renewable energy projects show quite high variability [22], [23], [24]. A commonly used cost parameter is the *levelized energy cost*. It is an economic assessment of the cost of the energy generating system including all the costs over its lifetime: initial investment, cost of operations and maintenance, and cost of fuel. It also considers the capacity factor, the percent of the time a generating system will be able to deliver its rated power. Figure 2 presented at the end of the report shows the levelized energy cost of new generation renewable and nonrenewable energy types [23]. According to this data, the levelized cost of biomass at 0.11 US Dollar per kWh is the lowest among all renewable energy sources, closely followed by geothermal and hydro. The cheapest cost among any source is 0.08 US Dollar per kWh for natural gas-fired advanced combined cycle.

8. Advantages of Biomass as a Source of Renewable Energy

The analyses presented in this report indicate that the biomass as a source of renewable energy has the following outstanding advantages as compared to other renewable energy types:

- **Large-scale universal utilization capability**

  The analysis presented in Table 4 evaluated the main forms of energy, namely chemical, electrical, light (electromagnetic), mechanical, and nuclear energy in terms of a concept we called “large-scale universal utilization capability” and defined as a qualitative aggregate of their following capabilities:

  - Overall efficiency for being converted to other forms of energy
  - Large-scale and long-range transmission capability
  - Transportation power (fuel) capability

  Within the limitations of this approach, the large-scale universal utilization capability of chemical energy came out as high, and electrical energy very high. All other energy forms fared low, little, or none according to our evaluation. Since presently known primary sources of electrical energy in the nature is limited to lightning and electric fish, the very high capability of electrical energy for large scale universal utilization is based on its secondary sources derived from other primary forms of energy available in the nature one of which is chemical energy. And biomass is the renewable alternative to fossil fuels as a source of chemical energy. Therefore, biomass both in itself and for generating electricity is an important renewable energy source.

- **Capability for providing sustainable, secure, competitive, and dependable energy**

  The analysis presented in Table 7 compared the renewable energy sources together with some of their harvesting technology alternatives regarding their overall present and potential capability for providing mankind sustainable, secure, competitive, and dependable energy.

  Within the limitations of the selected criteria and the values assigned to them by the author, this comparison indicated that small scale and large biomass technologies have the highest total capability grade of 82 and 73 respectively out of one hundred on a combined evaluation of global, national, commercial and household levels. The rest of the renewable energy types received grades ranging from 70 for photovoltaic solar to 35 for wave energy.

- **Lowest levelised cost among all renewable energy sources**

  Figure 2 placed at the end of the report indicates that the levelised cost of biomass at 0.11 US Dollar per kWh is the lowest among all renewable energy sources, closely followed by geothermal and hydro, while photovoltaic solar energy has the highest cost at 0.40 US Dollar per kWh.

- **Positive contribution to the environment**

  Except energy crops, all of the biomass sources are waste products. With the technology available today, their utilization as a source of energy not only contributes to the energy needs of humanity, but also helps to eliminate waste or minimize the unwanted impacts of waste on the environment.

  Even though waste with organic content is a good source of renewable energy, it should be emphasized that, a holistic approach to waste management not only includes conversion of appropriate waste to energy (energy recovery), but all of the following measures, listed from the most favorable to the least favorable [27]:

  - Prevention
  - Minimization
  - Reuse
  - Recycling
  - Energy Recovery
  - Disposal

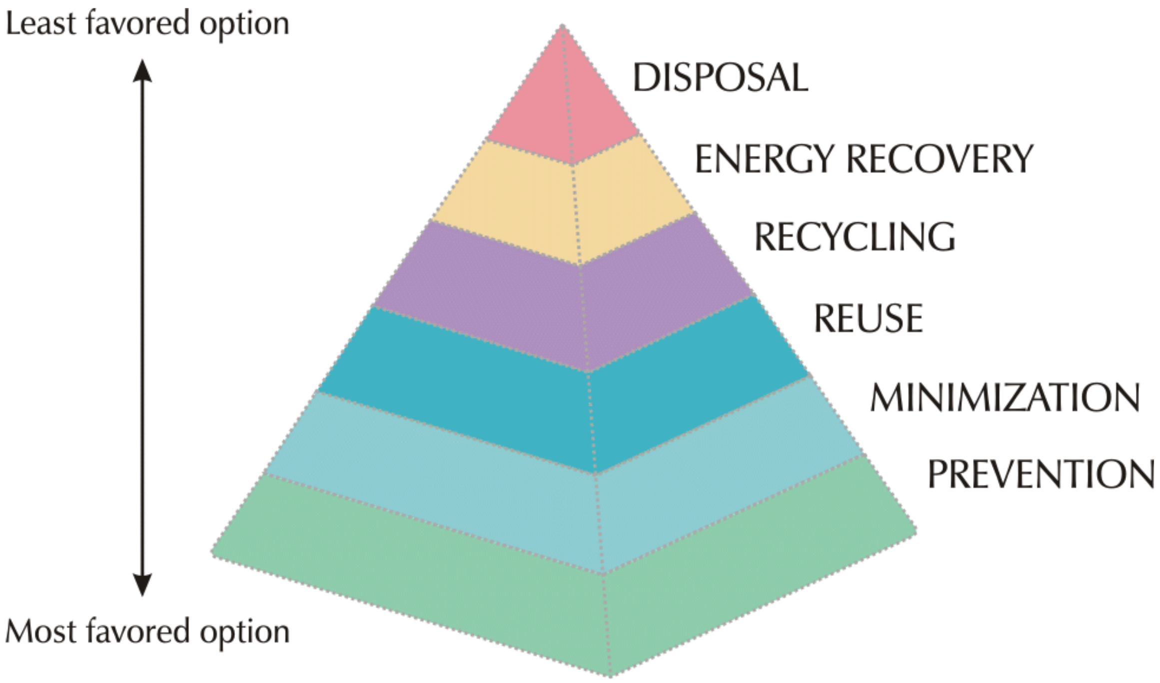

Figure 3. The holistic approach to waste management illustrated by the "Waste Management Pyramid". The base or foundation of the pyramid represents prevention of waste to start with. All the rest of the measures are built upon this foundation. Adapted after modifications from [27].

Prevention, namely avoiding the generation of waste all together is of course the most effective measure in waste management and hence forms the base of waste management activities. All of the rest of the waste management activities shall be built upon this base, one after the other. Therefore, the wider the base, the stronger the structure. Then, it is not surprising that we have another pyramid which we will call "Waste Management Pyramid" to illustrate this holistic approach to waste management, as presented in Figure 3 above.

9. Disadvantages of Biomass as a Source of Renewable Energy

Biomass has some disadvantages as compared other sources of renewable energy [32]:

- Biomass might have a cost to acquire, or a cost to make it available at the point of energy conversion as opposed to some other types of renewable energy such as wind and solar. Examples are:
    - All types of biomass might have some cost of transportation to the point of energy conversion. The larger the application scale, the larger this cost would be.
    - Energy crops have additional costs of planting, growing, and harvesting.
- More than one conversion step is necessary for generating electricity from most types of biomass sources, such as conversion to thermal, then to mechanical, then to electrical energy, as opposed to for example, conversion of solar energy to electricity in one step through photovoltaic cells. One exception is the direct conversion of biogas to electricity through fuel cells, but this technology is still under development.
- The term biomass covers a big variety of energy sources as covered in the next section. Even though all of the biomass types share the very basic property of being the outcome of living creatures, they are very different in their nature and composition. This requires specific technologies to be developed for each type of biomass. Therefore, specific know-how and expertise are required for harvesting energy from different types of biomass.

10. Biomass Types

EU Directive 2001/77/EC (RES-E) - on the promotion of electricity produced from renewable energy sources define biomass as follows [31]:

'Biomass' shall mean the biodegradable fraction of products; waste and residues from agriculture (including vegetal and animal substances); forestry and related industries; as well as the biodegradable fraction of industrial and municipal waste.

Biomass sources are very many. The following is a non-exhaustive listing of biomass material which could be utilized for converting to energy.

1. Domestic (municipal) waste
    a. Waste deposited in landfills
    b. Organic material separated from domestic waste

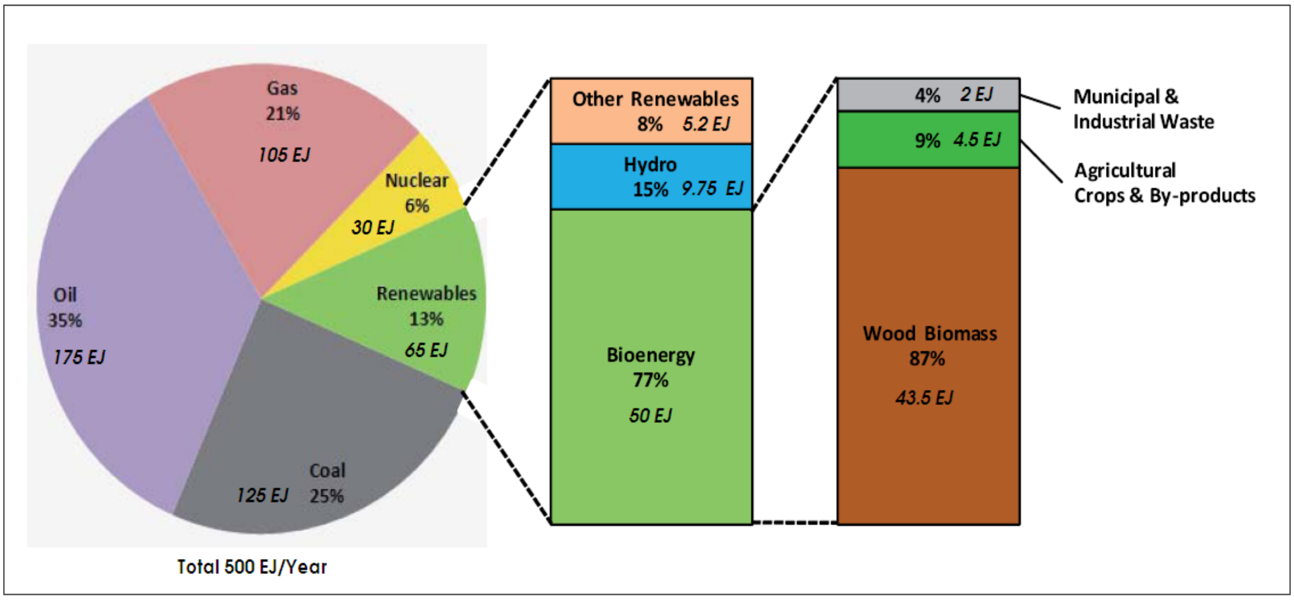

Figure 4. Contribution of biomass energy sources in the world primary energy mix in 2008. Adapted after modification from [32]. (1 Exajoule "EJ"= 10^18 Joule = 27.8x10^10 kWh) As an example for converting from EJ, an energy unit, to a power unit such as MW, consider the following example: Assume that the capacity factor of a biomass energy plant is 80%. This means that it will provide in one year that much of energy equal to its rated power multiplied by 0.8X8760 hours/year. According to the above figure, municipal and industrial waste contributed 2 EJ of energy in the year 2008. This is equivalent to about 55.6X10^10 kWh of energy. Therefore if this much energy were to be converted to electricity by plants of 0.8 capacity factor, their total installed capacity would have to be about 79,000 MW.

2. Sludge from sewage treatment
3. Animal manure and other animal husbandry waste
4. Animal processing waste
   a. Slaughter-house waste
   b. Fish market waste
5. Restaurant and hotel food and paper waste
6. Agricultural harvest (crop) waste
7. Garden and park waste
8. Forest residues and forest industries waste
9. Industrial organic waste
   a. Sugar industries waste
   b. Paper industries waste
   c. Leather and textile industries waste
10. Waste oils and fat
    a. Used lubricating oils
    b. Used cooking oils
    c. Waste animal fat
11. Food industry waste
    a. Olive processing waste
    b. Cheese whey and other dairy industry waste
    c. Potato chip production waste
    d. Catering (prepared meals) industry waste
    e. Starch production waste
    f. Fruit juice production waste
    g. Fish processing industry waste
    h. Bakery and confectionery production waste
    i. Canned and frozen food production waste
12. Energy crops
    a. Oil crops (such as rapeseed and jatropha)
    b. Vegetative crops (such as miscanthus, canary grass)
    c. Short rotation forest (such as salix, populus, eucalyptus)
    d. Macroalgea
13. Photosynthetic micro-organisms (such as microalgea and bacteria)

11. Global Biomass Availability and Utilization

The contribution of biomass energy sources to the global energy supply is estimated at about 50 EJ in the year 2008. (1 Exajoule = 10^18 Joule = 27.8X10^10 kWh). Figure 4 above shows that the percentage of this contribution to other sources of energy is currently about 10% [32].

It should be emphasized that for different countries the contribution of biomass energy could be very different. While biomass energy contributes only 3% of primary energy needs in industrialized countries, it provides 22% of the energy consumed in developing countries [32]. Therefore, local determinations should be made in every country or locality before counting on biomass availability.

It is estimated that [32], in the year 2050 the world energy demand might be between a low estimate of 600 EJ and a high estimate of 1000 EJ. Modeling studies indicate that world biomass demand might range from 50 to 250 EJ. On the other hand, technically possible potential for biomass energy potential could be up to a very optimistic value of 1500 EJ. However, a sustainable biomass potential varying in the range of 200 to 500 EJ would be more realistic. Therefore if appropriate actions are taken, biomass could, in its high estimate scenario, meet the demand for its kind, and remain only 20 % short of providing all the low estimate energy demand of the world. In order to realize the 200-500 EJ potential of the biomass energy, the following complex achievements must be realized globally, as adapted from [32]:

- The infrastructure needed for energy crops must be made available. This would require resolving human food and animal feed production competition issues regarding land and water resources use.
- The type of available energy crops must match the land and climate available for their growth so as to realize the biomass yield rates assumed in the estimates.
- Biomass production costs must be favorable as compared to the cost of other energy sources. As of today, US$4/GJ is regarded as an upper limit if biomass energy is to be widely deployed today in all sectors.
- Sufficient supply chain structure (logistics) for various biomass types must be available.
- Environmental and secondary sustainability issues of biomass production, such as water availability and quality, soil quality, biodiversity, etc. must be resolved.

Another estimate of global energy potential of various biomass types by the year 2050 are presented in Table 9 placed at the end of the report, as adapted from [30]. This table presents biomass types in order of decreasing global energy potential, in terms of an average value calculated at 1/3 up from the low estimates.

The following data collated from various sources give an indication of the extent of biomass utilization:

- China has around 25 million and India about 4 million farm households that use anaerobic digesters generating biogas which is employed for cooking and lighting, while the total world count is estimated at around 30 million units [38].
- Biomass power plants exist in over 50 countries around the world and supply a growing share of electricity. Table 10 and Table 11 at the end of the report present some figures regarding the amount of electricity generated in various countries from all of the biomass sources and from biogas alone [38].

12. Biomass-to-Energy Conversion Technologies

The harvesting of biomass energy takes place in a complex chain of conversion steps. Table 12 placed at the end of the report presents a condensed display of the various types of biomass, composition of biomass sources, various initial processes employed in the conversion chain, intermediate products, final energy conversion and other related technologies, and final products. About 30 different biomass types listed in the previous section has been summarized in 13 classes in this table in the first row. Each biomass type contains many of the 13 components listed in the second row. Many of the biomass types can be converted to one or more of about a dozen intermediate products listed in the fourth row by using one or more of 13 different initial conversion processes shown in the third row. The intermediate products can finally be converted to mechanical and electrical energy, transportation fuels, heating and cooling, organic fertilizers, charcoal, specialty chemicals, and carbon credits listed in the sixth row by using one or more of the technologies in row five. If we were to show all the possible routes going from biomass material to final products, it would be impossible read Table 12. As an example, consider some of the routes in the case of a landfill gas-to-energy application:

- Domestic waste would contain all of the components stated in the second row.
- All of the components except lignin, plastics, metals, and glass would undergo spontaneous anaerobic digestion in the landfill, however at widely varying speeds.
- Gaseous intermediate products of the anaerobic digestion would be CH4 (~50%), CO2 (~45%), water, H2S and siloxane gases, and hundreds of other gases in trace amounts.
- After some pre-treatment, all of the gaseous intermediate products would be sent to a spark ignition engine and alternator set which will convert the energy in the CH4 (methane) gas first to mechanical and then electrical energy.
- Waste heat from the exhaust of the engine could be used for domestic or industrial heating, or be converted to additional electrical energy through an ORC system. The “thermoacoustic heat transformer” under development for commercialization [34] could increase the temperature and hence the quality of the waste heat, making higher efficiencies from waste heat harvesting systems possible.
- Waste heat in the jacket water plus waste heat from the ORC system could be utilized to obtain domestic or industrial cooling by the use of an absorption or adsorption cooler.
- Carbon dioxide from the exhaust gas of the engine could be purified, compressed or liquidified, and supplied to the food industry or other industrial markets.
- Because methane gas, which is 21 times more harmful than carbon dioxide, is converted to carbon dioxide and then released to the atmosphere, carbon credits would be generated, and these could be supplied to Kyoto Protocol markets or voluntary emission reduction markets. It should be noted that a landfill gas-to-energy project generates about 10 times more carbon credits per MW of installed capacity as compared to a wind energy project. [35], [36].

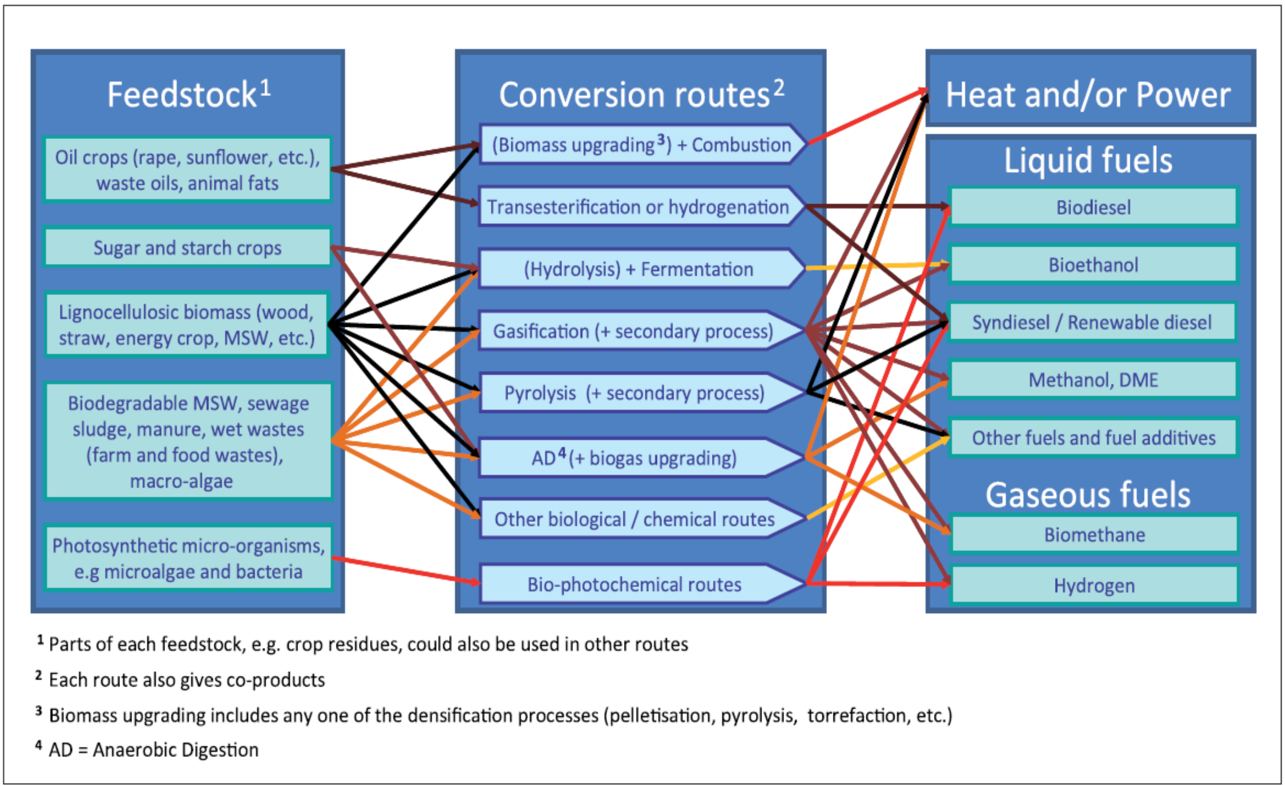

Figure 5. A schematic view of the conversion routes for a limited number of biomass classes. Adapted from [32]

- Last, but not the least, a landfill gas-to-energy project would minimize the unwanted environmental impacts of a deposit of waste such as landslides, fires, explosions, foul odors, etc. in the neighboring communities, and generate about two dozen local job positions per plant, at all competency levels ranging from plant managers to low level labor.

Figure 5 above presents a rather simplified schematic view of the conversion routes for a limited number of biomass classes [32]. As it is observed from this figure, possible conversion routes are too numerous.

We can summarize biomass-to-energy conversion technologies as follows:

1. Spontaneous anaerobic digestion in landfills.
2. Engineered anaerobic digestion.
3. Thermal processing methods:
    - Combustion (Incineration).
    - Pyrolysis.
    - Gasification.
    - Torrefaction for refuse derived fuel production.
4. Ethanol fermentation for fuel production.
5. Weak acid and trans-esterification for biodiesel production.
6. Thermo-catalytic reactions for fuel synthesis.

In the following paragraphs, we will provide brief information for the first three of the above technology groups.

12.1 Anaerobic Digestion Fundamentals

Except lignin and plastics, any organic substance kept in a humid and anaerobic (oxygen free) environment start to decompose and generate a combustible gas mixture through a series of processes collectively called the “anaerobic digestion”.

A simplified illustration of the biological and chemical processes taking place in anaerobic digestion is presented in Figure 6 on the next page. The process stages are:

- ***Hydrolysis*** which generates sugars, fatty acids, and amino acids, by the help of a group of *hydrolytic bacteria*.
- ***Acidogenesis*** which generates carbonic acids, alcohols, hydrogen, carbon dioxide, ammonia, and hydrogen sulphide by the help of a group of *acidogenic bacteria*.
- ***Acetogenesis*** which generates acetic acid and more hydrogen and carbon dioxide, by the help of a group of *acetogenic bacteria*.
- ***Methanogenesis*** which generates methane and carbon dioxide, by the help of a group of *methanogenic bacteria*.

The above four groups of bacteria are all anaerobic micro organisms which means that they thrive in environments which are free from oxygen. They are mutually beneficial and interdependent, i.e. removing inhibitory products of other bacterial groups and/or producing substances for other bacterial groups. The important point is therefore, that the process is dependent on the correct balance of each of these groups of bacteria, because any one group will not operate alone [49].

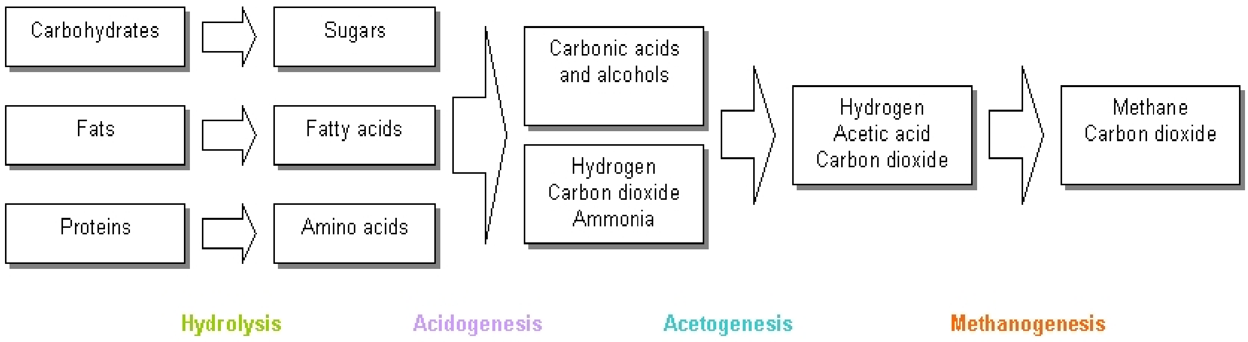

Figure 6. The four stages of the anaerobic digestion and the various substances generated in each stage. Adapted from [46]. It should be noted that in addition to the macro-constituents shown in this figure, hundreds of other gases are generated in trace amounts in various stages of anaerobic digestion [29].

12.2 Spontaneous Anaerobic Digestion in Landfills

In landfills, domestic waste is deposited and daily covered by earth. Within a year, all the oxygen trapped in the waste will be consumed by the *aerobic bacteria* which live and thrive with oxygen. Then, anaerobic bacteria will step in and start to generate what is called "landfill gas" through the anaerobic digestion process described above. Landfill gas contains methane gas CH4 at a concentration of 35-55%, the remainder being carbon dioxide and small amounts of other gases. The gas generation peaks within a year or two,and then decays exponentially over tens of years, depending on the rain fall and average temperature in the region.

Further details have been presented in the previous section. For a detailed description of a landfill gas-to-energy project, see [47].

12.3 Engineered Anaerobic Digestion

Engineered anaerobic digestion technology can be utilized for the generation of energy from almost all types of biomass except plastics, and woody material containing lignin. For this purpose, biomass is placed in vessels (tanks) of appropriate size, called a digester, and the anaerobic digestion process is achieved under controlled conditions. The main parameters which are monitored and controlled are carbon/nitrogen ratio, temperature, and pH value of the digester contents. The term “anaerobic digestion” is usually reserved for this technology.

Anaerobic digesters can be designed and operated in many different process configurations which can be classified as follows [50]:

- Water dilution of the feedstock:
  - Wet technology with 10-15 % solids
  - Dry technology with 20-40 % solids
- Number of stages (vessels):
  - Single tank, combining all the four process stages of the anaerobic digestion in one tank
  - Two tanks, having the first two process stages in one tank and the last two in a second tank.
- Operating temperature:
  - ***Mesophilic*** range around 35 °C, making use of the mesophilic type of bacteria
  - ***Thermophilic*** range around 55 °C, making use of the thermophilic type of bacteria
  - Two temperature system, with the first tank operating at thermophilic, and the second at mesophilic temperatures
- Material feeding:
  - Batch
  - Continuous
- Type of digester container:
  - Covered lagoon
  - Plug flow
  - Complete mix
  - Fixed film (A fixed film digester vessel is filled with an inert medium or packing, usually plastics, that provides a very large surface area for microbial growth.)

Figures 7 through Figure 10 placed at the end of the report present some pictures of various types of anaerobic digesters.

12.4 Thermal Processing Methods:

Thermal processing of biomass for energy recovery include the following main methods [27]:

- **Combustion (Incineration)**

Combustion of biomass with energy recovery is the most developed one among other thermal processing methods. In this method, the thermal reactions take place at a temperature of 950°C to 1100 °C with excess air (“lean burning” with internal combustion engine terminology). The output of this process is CO2, H2O, ash, and a large number of trace gases which are quite harmful to the environment, and fly ash & flue gas must be aggressively cleaned. The availability and reliability of the biomass

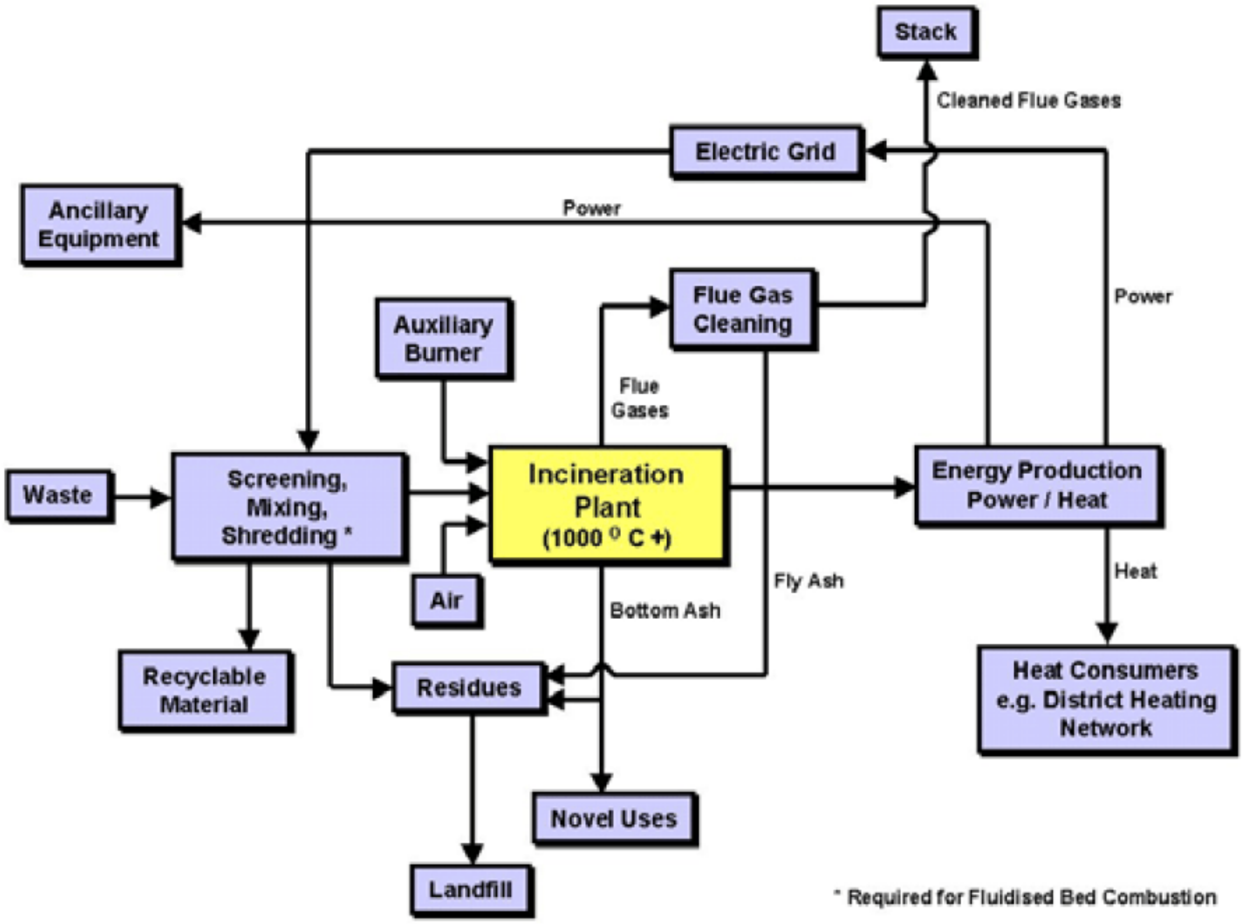

Figure 11. A simplified process flow diagram of a typical biomass combustion (incineration) plant with energy recovery. Adapted from [27].

combustion plants are comparable to modern power stations operating on fossil fuels. With few exceptions, these plants can accept residential and commercial waste without the need for pre-processing. Modern combustion plants can meet the latest environmental standards as set by EU and national governments but utilize costly flue gas and fly ash treatment systems. Figure 11 above presents a simplified process flow diagram for the combustion method. For further attributes of the combustion method, see Table 13, placed at the end of the report.

- **Pyrolysis**

Pyrolysis is a thermal pre-treatment method which can transform biomass into a low to medium energy combustible gas (a mixture of CO and H2), some liquid fuel, and a solid residue consisting partly of inert materials (ash like), partly of a so-called “char”. The pyrolysis process is similar to making of charcoal practiced by mankind since very old times. In charcoal making, the solid residue was valued and the gaseous and vaporized liquid products were discharged to air. Since the year 1800, mankind used gas obtained by the pyrolysis of *coal* for home and city lighting. During World War II, due to the allocation of petroleum based fuels to military operations, “wood gas” powered vehicles were constructed and utilized on a large scale, reportedly about one million vehicles globally of which at least half a million manufactured in Germany [53], [74]. Figure 12 placed at the end of the report presents pictures of a selection of historical and recent wood gas powered vehicles.

Even though pyrolysis has been known so long, and several small-scale energy generation plants have been built in the last decades, large-scale pyrolysis plants designed to treat domestic waste are yet to prove long term successful operating experience [27].

The pyrolysis process requires that the waste feed be reduced in size (shredded) prior to thermal treatment under pressure at a temperature between 500°C to 700°C without any oxygen. The gas produced can either be pre-treated before combustion, or flue gas produced after the combustion must be extensively cleaned. Normally, pyrolysis gas is utilized in external combustion systems such as those for steam or hot water production, or Stirling engine. Figure 13 below presents a simplified process flow diagram for the pyrolysis method. For further attributes of the combustion method, see Table 13, placed at the end of the report.

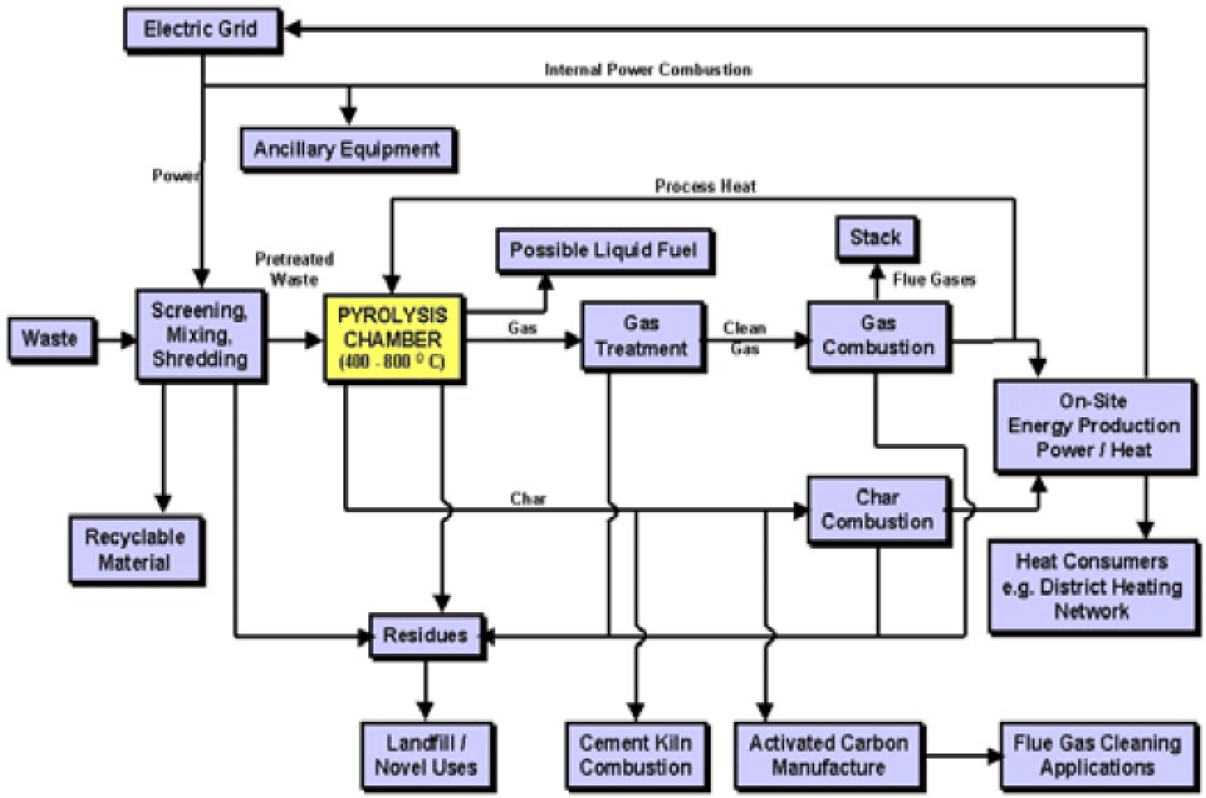

Figure 13. A simplified process flow diagram of a typical pyrolysis plant. Adapted from [27].

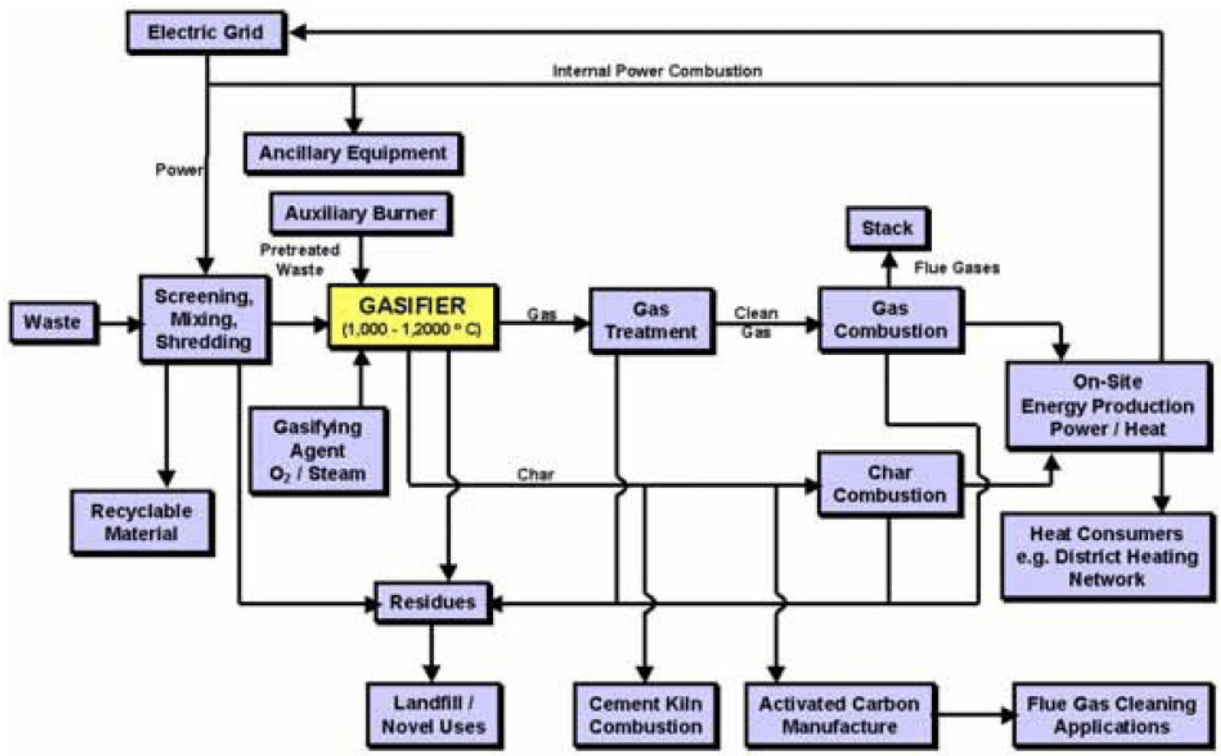

Figure 14. A simplified process flow diagram of a typical gasification plant. Adapted from [27].

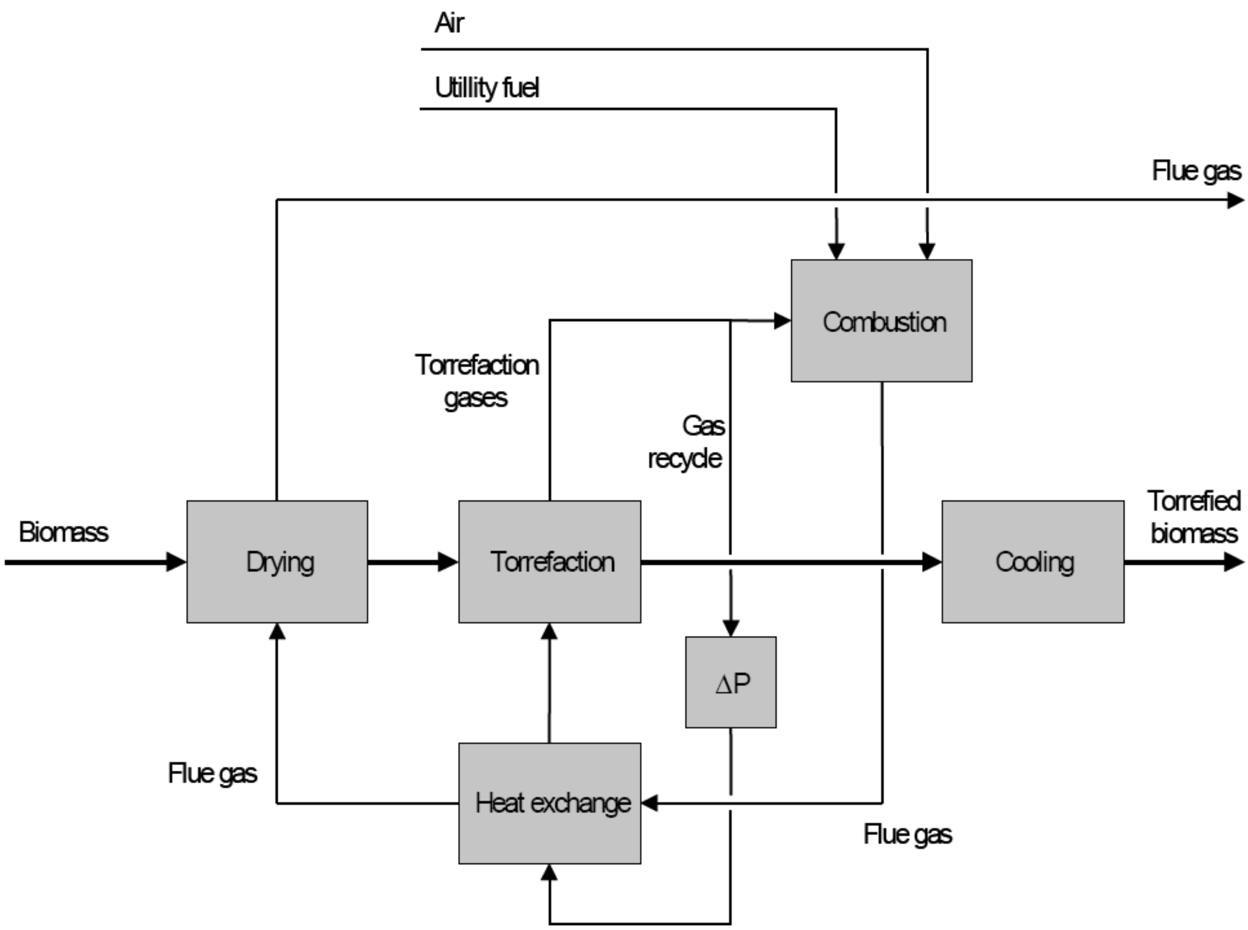

Figure 15. A simplified process flow diagram of a typical torrefaction plant. Size reduction of the incoming biomass and pelletization of the outgoing torrefied biomass are not shown. A flue gas treatment system would also be needed for the proper discharge to atmosphere. Adapted from [54].

- **Gasification**

The gasification process is similar to the pyrolysis process, but it takes place at higher temperatures between 800°C to 2000°C with limited and controlled oxygen exposure. As a result, the char residue remaining in the pyrolysis process is also gasified. If pure oxygen is used in the final stages of the process, temperatures will reach a level where the ash residues are vitrified into a glass like substance which can harmlessly be used as filler material without any environmental concern. There is no liquid output. Similar to the pyrolysis process, the gas produced (a mixture of CO and H2) can either be pre-treated before combustion or flue gas must be extensively cleaned. Normally, this gas is utilized in external combustion systems such as those for steam or hot water production, or Stirling engine. If fully cleaned from tar particles it could also be used in lean-burning internal combustion engines.

Figure 14 on the previous page presents a simplified process flow diagram for the gasification method. For further attributes of the combustion method, see Table 13, placed at the end of the report.

- **Torrefaction for refuse derived fuel production**

The torrefaction process is again similar to pyrolysis, but at lower temperatures between 200°C to 300°C under atmospheric pressure, without any oxygen exposure. During this process, various properties of the biomass changes to result in a better material for subsequent combustion and gasification.

This process is yet under development and is reported to convert a broad range of biomass streams, such as wood chips, agricultural residues and various residues from the food and feed processing industry into a form of processed biomass with the following desirable properties [54]:

- Energy density significantly higher than the original material.
- Lower power requirement for grinding for pelletization.
- Water repellant nature.
- Elimination or reduction of biological degradation and spontaneous heating.
- Enabling outdoor storage.

Upon torrefaction, a typical woody biomass would keep 70% of its dry mass, containing 90% of the initial energy content. The other 30% of the dry mass is converted into torrefaction gases and vapors, which contain about 10% of the energy of the biomass. An energy densification with typically a factor of 1.3 can be attained.

A complete system will first reduce the size of the biomass, and if the biomass moisture content is higher than 15-20% would include a dryer before the thermal reactor. Torrefaction gases can be used for both drying and the torrefaction process. Depending on the need, externally supplied fuel will be required. After torrefaction, the material is ground into suitable powder size and pelletized for use as a high quality refuse derived fuel [54].

Figure 15 on the previous page presents the process flow diagram of a typical torrefaction system, excluding the size reduction and pelletization.

12.5 Safety considerations in energy conversion activities from biomass

Many of the energy conversion and utilization activities from biomass result in the generation of various gases which could seriously be harmful to health and/or cause extensive property loss. Therefore, the following safety precautions should seriously and aggressively be executed irrespective of the scale of the project or whether such activities are of hobby or professional nature.

Various biomass energy conversion activities generate the following gases in significant amounts with the briefly stated considerations:

- **Methane** (CH4) is a highly combustible gas at concentrations between 5% to 15% in air. It is not poisonous itself in small concentrations, but would displace oxygen in confined spaces and could cause asphyxiation. Since it is lighter than air at ambient temperature, detectors for this gas should be placed at elevated locations in confined spaces [61].
- **Hydrogen** (H2) is a highly combustible gas. Its flame, while being extremely hot, is almost invisible, and thus can lead to accidental burns and property damage. It is not poisonous itself in small concentrations, but would displace oxygen in confined spaces and could cause asphyxiation [65].
- **Carbon dioxide** (CO2) is toxic in small amounts, and continuous exposure should be limited to 0.5% [62] Short term exposure to concentrations exceeding 4% could be immediately dangerous to life and health.
- **Carbon monoxide** (CO) is colorless, odorless and tasteless, but very toxic in small concentrations. It is slightly lighter than air, but due its high toxicity should be detected at all elevations in confined spaces. Long-term exposure level limit is 50 ppm (parts per million) [63]. A good background in carbon monoxide safety is an absolute requirement before entering any biomass energy conversion activity. It has flammability limits of 12.5% to 74% in air.
- **Hydrogen sulphide** (H2S) is a very highly toxic gas. Being heavier than air, it tends to accumulate at the bottom of poorly ventilated spaces. Although very pungent at first, it quickly deadens the sense of smell, so potential victims may be unaware of its presence until it is too late. Safe exposure limit for no more than 10 minutes is 10 ppm. It is considered immediately dangerous to life or health at concentrations above 100 ppm [64]. Concentrations over 1000 ppm can cause immediate collapse with loss of breathing, even after inhalation of a single breath. It is a flammable gas. Similar to carbon monoxide, a good background in hydrogen sulphide safety is an absolute requirement before entering any biomass energy conversion activity. It has flammability limits of 12.5% to 74% in air [64].

Above are only a few of the potentially harmful gases encountered in the field of biomass energy conversion. Furthermore, their coverage in this report is only introductory and not intended to be enough for the safety requirements. A good training in the proper handling of the above gases and other substances involved in biomass activities, of however casual or short in duration they be, is necessary for human safety and property protection.

13. Business, Research and Development Opportunities in the Renewable Energy Field

Business opportunities in the renewable energy industry are numerous and could be very satisfying both professionally and financially. Local experts in developing countries will have better a opportunity for competing with foreign expertise especially in the consultancy services, installation and maintenance services for small systems, and systems and components trading at the retail, wholesale, national/regional distribution and manufacturers representation levels.

- Consultancy, engineering, and training services:
  - Promotion of energy consciousness at the household, small and large enterprise, and government levels.
  - Assessment of various renewable energy sources potential at the national and regional levels.
  - Wind, hydro, biomass, and other renewable energy sources capacity surveying at the project level.
  - Project feasibility studies, technical and financial.
  - Support for energy generation licences, purchase contracts, and technical approvals from government offices.
  - Life cycle procurement and contracting support.
  - Plant design, engineering, and controlling works.
- Installation and maintenance services for small systems.
- Systems and components trading at the retail, wholesale, national/regional distribution and manufacturers representation levels.
- Construction and/or equipment furnishing sub-contracting for major projects.
- Turn-key contracting for major projects.
- Manufacturing of systems and components under license agreements or by reverse engineering of products with expired patents.
- Adaptation of existing systems, and/or manufacturing of systems and components in ways or versions suitable for local/national capabilities (appropriate technology adaptation [37]).

- Research and development (R&D) for improved versions of already commercialized systems and components.
- Research and development on newly emerging systems and components which are not yet commercialized.
- Research and development of original concepts and ideas.

It should be noted that, above listed business activities could be realized in all of the levels of the energy pyramid (see Figure 1), namely, rational use of energy and energy efficiency in addition to renewable energy conversion and utilization.

14. Summary and Conclusions

Mankind has utilized what is now called renewable energy since pre-historic times, namely biomass, wind, water, and biomechanical energy sources. With the advent of widespread coal mining, and petroleum and natural gas exploitation, humankind has started to consume these nonrenewable sources without much consideration of their depletion and the resultant environmental damages. Now, mankind thinks that the non-renewable energy sources are really about to be exhausted. Now, mankind thinks that all this consumption is not only destroying the environment in their homeland, but could be taking the whole globe to some grave destination called global warming. Finally, the world appears to be after sustainable, secure, competitive and dependable energy. It is now widely understood that these criteria are satisfied to a large extend by renewable energy sources.

The "energy pyramid" in Figure 1 illustrates the holistic approach to energy management as a combination of the utilization of renewable energy resources together with the rational use of energy and energy efficiency measures.

A number of important concepts which must be well comprehended when evaluating or comparing energy generating technologies and power plants are explained in Text Boxes 1 thru 3. These are:

- Power efficiency and energy harvesting efficiency.
- Availability factor and reliability factor.
- Capacity factor and load factor.

A comparison of the main forms of energy found in the nature, namely the chemical, electrical, light (electromagnetic), mechanical, nuclear, and thermal energy is presented in Table 4, in terms of a number of criteria such as their primary, secondary, and renewable sources, storage capabilities, conversion technologies and conversion efficiencies, transmission capability, transportation fuel power capability, and large-scale universal utilization capability.

A comparison of a number of renewable energy sources and harvesting technology alternatives is presented in Tables 7 and 8 regarding their overall present and potential capability in providing mankind sustainable, secure, competitive, and dependable energy.

The analyses presented in this report indicate that the biomass as a source of renewable energy has a number of outstanding advantages as compared to other renewable energy types. These are:

- Large-scale universal utilization capability.
- Capability for providing sustainable, secure, competitive, and dependable energy.
- Lowest levelized cost among all renewable energy sources.
- Positive contribution to the environment, because except energy crops, all of the biomass sources are waste products.

Biomass has some disadvantages as compared other sources of renewable energy, and these are:

- Biomass might have a cost to acquire, or a cost to make it available at the point of energy conversion.
- More than one conversion step is necessary for generating electricity from most types of biomass sources.
- Biomass types are very different in their nature and composition. This requires specific technologies and specific know-how and expertise to be developed for harvesting energy from different types of biomass.

The "waste management pyramid" in Figure 3 illustrates that a holistic approach to waste management not only includes conversion of appropriate waste to energy, but all of the following measures, listed from the most favorable (at the base of the pyramid) to the least favorable (at the tip of the pyramid): Prevention, minimization, reuse, recycling, energy recovery, and disposal.

There are more than 30 different sources of biomass suitable for energy generation. About 10% of the global energy need is provided by biomass sources. However, it should be emphasized that for different countries the contribution of biomass energy could be very different. While biomass energy contributes only 3% of primary energy needs in industrialized countries, it provides 22% of the energy consumed in developing countries Therefore, local determinations should be made in every country or locality before counting on biomass availability.

It is estimated that in the year 2050 the world energy demand might be between a low estimate of 600 EJ and a high estimate of 1000 EJ. To meet part of this demand, a sustainable biomass potential varying in the range of 200 to 500 EJ could be possible by the help of the large scale production of energy crops. Without energy crops, the contribution of biomass would be around 55 EJ.

The harvesting of biomass energy takes place in a chain of conversion steps. Figure 10 is a condensed display of the various types of biomass, composition of biomass sources, various initial processes employed in the conversion chain, intermediate products, energy conversion and other related technologies, and final products and outcomes.

There are numerous business, research and development opportunities in the renewable energy industry which could be very satisfying both professionally and financially. Local experts will have a better chance for competing with foreign expertise especially in the consultancy services, installation and maintenance services for small systems, and systems and components trading at the retail, wholesale, national or regional distribution, and manufacturers representation levels.

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Table 4. A comparison of various ***forms of energy.*** The "large-scale universal utilization capability" at the last column is defined as a qualitative aggregate of the four features marked by (# 1). *Blue and italic text* indicates features which highly distinguish chemical and electrical energy from other energy forms.

FORM OF ENERGY	Primary Sources and Typical Exploitable Power Levels Per Energy Conversion Plant	Derived (Secondary) Sources	Capacity Factor of the Primary Source	Available Energy Storage Mediums	Energy Storage Scale and Storage Duration (# 1)	Single-Step Conversion Technologies to Other Forms of Energy	Conversion Technology Examples & Efficiency of Conversion to Electrical Energy (#1)(#4)	Large-scale Long-distance Transmission Capability (# 1)	Transportation Power (Fuel) Capability (# 1)	Large-Scale Universal Utilization Capability
Chemical Energy "C"	Fossil fuels (# 2): (GW level) Biomass from living creatures: (MW level)	"Organic" fuels: bio-gas and bio-diesel. Synthetic fuels: H2, CO, ethanol and methanol	High	Storable in their original form	*Very high scale for very long time*	E: Fuel cell L: (# 5) M: Muscle T: Combustion	*Gen-Set: C/T/M/E 35~45%;Fuel Cell: C/E 55 %;* Primary battery: C/E 2 % (# 8)	*High, by transmitting fuels*	*Very high, through solid, liquid and gaseous fuels*	***HIGH*** (That's why the global contention on petroleum)
Electrical Energy "E"	Lightning: (0.36 to 3.6 kWh per flash). Bio-electrical sources like electric fish: (~ W level)	Alternators, batteries, photovoltaic & fuel cells, thermoelectric, magneto-hydro-dynamic & piezo-electric generators	Negli-gible	Rechargeable batteries, hyper capacitors	~ MWh scale for months	C: Electrolysis L: Fluorescent lamp, LED etc. M: Electric motor T: Resistance, electric arc	*AC/DC/AC: 90+ %* *Transformer: 98 %* *E/L 20 %* (# 9) *E/C 50~85 %* (#10) *E/M 98 %* (# 11) *E/T ~100 %* (# 12)	*Very high, through high voltage transmission lines*	*High, through storage mediums*	***VERY HIGH*** (That's why "conversion to energy" means conversion to electricity)
Light (Electro-magnetic) Energy "L"	Solar: (MW level) Bio-luminescent sources like firefly & jellyfish: (μW ~ mW level)	Incandescent and Luminescent light sources (Usually not for energy applications)	Low	Phosphores-cent materials (Usually not for energy applications)	μWh or mWh scale for minutes to hours	C: Photosynthesis E: Solar cell M: Photon engine T: Solar water heater	Photovoltaic: L/E % 14~20 Solar thermal: L/T/M/E % 10 ~ 20	None	None, except for solar pow-ered vehicles during sunny hours	Very little
Mechani-cal Energy "M"	Hydro: (GW level) Wind, Wave, Tidal: (MW level) Bio-mechanical: (kW level)	Heat engines, electric motors	Hydro with large dam: Medium. Others: Low	Flywheels, compressed gases, springs, pumped-back hydro	~100 kWh scale for hours for flywheels and unlimited time for compressed gases and springs. Very high scale for many months for pumped-hydro	C: ? E: Alternator, magneto-hydro-dynamic & piezo-electric generators L: (# 6) T: Friction heater	Alternator: M/E % 97+ Magneto-hydro-dynamic generator: M/E % 22 Piezoelectric: M/E % 4	Little, only by transmitting the storage mediums	Low, for flywheels and compressed gases. Low, for wind during windy hours.	Little
Nuclear Energy "N"	Naturally occurring radioactive substances (fission) (# 2) (GW level)	Fusion (future) (# 3): Also, induced radioactive substances (# 3)	High	Storable in their original form	Very high scale for very long time, but highly risky in the form of refined radioactive material	L: (# 7) C: ? M: ? T: Fission, fusion E: ?	High Temp. Gas Cooled Reactor: N/T/M/E % 33 ?	Very high, by transmitting radioactive substances, but highly risky	Little, because of high risks	Low, together with risks
Thermal Energy "T"	Geothermal (# 3): (MW level) Ocean-thermal: (MW level) Bio-thermal: (mW ~ W level)	Combustion of fossil fuels & biomass, solar absorbers, electric heaters, heat pumps, nuclear reactions	High	Sensible heat: Water, oil. Latent heat: Phase change materials	~ 10 kWh scale for hours	L: Very hot object C: Endothermic reaction M: Heat engine E: TEG (# 13) E: AMTEC (# 14)	Steam and Organic Ranking Cycle Turbine: T/M/E % ~13 TEG: T/E % 5-7 AMTEC: T/E % 20	Little, only by transmitting the storage mediums	Little, through storage mediums	Very little

Notes: All energy sources stated above are ***renewable*** except as indicated by (#2): *non-renewable (depletable)*, and (#3): *practically inexhaustible.* (#4): All conversions starting from primary sources, except electrical energy from derived (secondary) sources. (#5): Chemoluminescence (#6): Triboluminescence (#7): Radioluminescence, all currently exploitable only at very low power (μW ~ mW) levels. (#8): Primary batteries produce only about 2% of the power used in their manufacture. (# 9): LED lamp. (# 10): Rechargeable batteries. (# 11): Electric motor. (# 12): Resistance heater. (#13): Thermo electric generator. (#14): Alkali Metal Thermal Electric Converter. Data sources: [11], [12], [14], [15], [44], [45], [48], [55], [56], [57], [58], [59].

Table 7. A comparison of renewable energy sources with some harvesting technology alternatives on the global, national, commercial and household levels. See Figure 2 for financial comparisons. A grade out of 5 is assigned to each of the 12 comparison criteria based on a combined evaluation of all the levels. For the criteria marked with an asterisk (*),the grade is inversely assigned. Energy types are listed in alphabetical order. Assignment of the grades are explained in Appendix A.

Applicable Level Abbreviations: G: Global N: National C: Commercial H: Household	**Applicable Levels**	**Biomass Large Scale**	**Biomass Small Scale**	**Enhanced Geothermal**	**Hydro-Geothermal**	**Hydro large scale with dam**	**Hydro small scale, run-of-the-river**	**Solar Photo-voltaic**	**Solar Concen-trated PV**	**Solar Thermal Electric**	**Tidal**	**Wave**	**Wind**
Environmental friendliness (minimum harm)	G, N	4	5	4	4	2	4	5	5	4	3	3	4
Positive contribution to the environment	G, N, C, H	5	5	0	0	4	0	0	0	0	0	0	0
Worldwide availability	G, N, C	5	5	3	1	2	3	4	4	4	1	2	3
Availability close to points of use	N, C, H	4	5	2	1	1	3	5	5	4	1	2	2
Plant size scalability	G, N, C, H	3	2	1	1	2	3	5	4	3	1	1	4
Current technological capability	G, N, C, H	3	5	1	4	5	5	3	2	2	1	1	4
Potential for technology improvement	G, N, C	3	1	3	1	1	1	5	5	4	2	2	4
Capacity factor	G, N, C, H	4	4	5	5	3	1	1	2	2	1	1	2
Unpredictable source variability (*)	G, N, C, H	4	5	5	5	3	1	3	3	3	5	1	1
Land area occupation (*)	N, C, H	3	3	3	3	1	3	2	2	2	4	5	5
Implementation technology level (*)	N, C, H	3	5	1	2	1	3	4	3	3	2	2	3
Project implementation time (*)	N, C, H	3	4	1	2	2	3	5	3	3	1	1	3
Total Grades with Equal Weight on All Criteria		44	49	29	29	27	30	42	38	34	22	21	35
Total Grades as Percent of Full Grade (5x13=65)		**73**	**82**	48	48	45	**50**	**70**	**63**	**57**	37	35	**58**

Table 9. Some estimates of global energy potential of various biomass sources by 2050. It should be noted that, biomass potential for specific regions or countries could be very different than the global estimates presented here. Energy figures stated refer to the sum of all forms of utilization potential such as thermal, electrical, fuel, etc. Adapted from [30].

BIOMASS CATEGORY	**GLOBAL ENERGY POTENTIAL IN BIOMASS BY 2050 (EXAJOULES/YEAR)**		**MAIN ASSUMPTIONS AND REMARKS** (1 Exajoule "EJ" = 10^18 Joule = 27.8X10^10 kWh)
	Low and High Estimate	**Average at 1/3 from the Low Estimate**	
Energy crops farming on surplus agricultural (premium quality) land	0 - 700	230	A delicate balance must be maintained between energy generation, and food and feed production. Subject to water availability, rationalization of agriculture and climate variations.
Energy crops farming on marginal (low quality) land	<60 - 110	77	Same as above, however less subject to competition from food and feed production.
Forest residues	30 - 150	70	The sustainable energy potential of the world's forests is unclear – some natural forests are protected. Low estimate includes limitations with respect to logistics and strict standards for removal of forest material. High estimate is based on technical potential. Figures include processing residues.
Residues from agriculture	15 - 70	33	Subject to climate variations.
Animal manure	5 - 55	22	Use of dried manure. Low estimate based on global current use. High estimate: technical potential. Utilization (collection) in the longer term is uncertain
Various organic wastes	5 - 50	20	Estimate on basis of literature values. Strongly dependent on economic development, consumption and the use of bio-materials. Figures include the organic fraction of municipal solid waste and waste wood. Higher values possible by more intensive use of bio-materials.
COMBINED ENERGY POTENTIAL OF GLOBAL BIOMASS SOURCES (EJ/YEAR)	55 - 1135 **(200 - 400)**	415 **(270)**	Most pessimistic scenario: no land available for energy farming; only utilization of residues, waste and manure. Most optimistic scenario: intensive agriculture concentrated on the better quality soils. In parentheses: average potential in a world aiming for large-scale deployment of energy from biomass.

Table 10. Electricity Generated from all of the biomass sources. Adapted from [38]. (Capacity Factor assumed to be 80% for the conversion between cited energy output per year to installed power and vice versa. 1 T=1X10^12 , 1 G=1X10^9, 1 M=1X10^6, 1k=1X10^3 .)					
Country	Year	Energy Output per Year (Cited in the Literature)	Corresponding Approximate Installed Power (MW)	Installed Power (Cited in the Literature)	Corresponding Approximate Energy Output per Year (Twh/year)
USA	2009			8500 MW	60 TWh/year
Europe	2009			7000 MW	49 TWh/year
USA	2007	42 TWh/year	5993 MW		
Brazil (Sugar Mills)	2009			4800 MW	34 TWh/year
China	2009			3200 MW	22 Twh/year
Japan	2007	16 TWh/year	2283 MW		
Germany	2007	10 TWh/year	1427 MW		
Finland	2008	20% of electricity consumption obtained from Biomass			
Germany	2008	5.3% of electricity consumption obtained from Biomass			

Table 11. Electricity Generated from biogas alone. Adapted from [38]. (Capacity Factor assumed to be 80% for the conversion between cited energy output per year to installed power and vice versa. 1 TW=1X10^12 W, 1 GW=1X10^9 W, 1 MW=1X10^6 W, 1kW=1X10^3 W.)					
Country	Year	Energy Output per Year (Cited in the Literature)	Corresponding Approximate Installed Power (MW)	Installed Power (Cited in the Literature)	Corresponding Approximate Energy Output per Year (Twh/year)
OECD	2008	30 TWh/year	4281 MW		
Germany	2009			1700 MW	12 TWh/year
USA	2008	7 TWh/year	999		
UK	2008	6 TWh/year	856		
Italy	2008	2 TWh/year	285		
Thailand	2009			51 MW	0.36 TWh/year

Table 12. A condensed display of the various types of biomass, composition of biomass sources, various initial processes employed in the conversion chain, intermediate products, final energy conversion and other related technologies. Adapted after modifications from [25], [32] and [33].

BIOMASS SOURCES	Domestic waste	Sewage sludge	Animal manure	Animal processing waste	Crop waste	Forest industry waste	Garden & park waste	Hospitality industry waste	Food industry waste	Other industry organic waste	Used industrial & cooking oils & fat	Energy crops & algae	Photo-synthetic micro-organisms
COMPONENTS OF BIOMASS SOURCES	Cellulose	Hemi-cellulose	Lignin	Starch	Proteins	Sugars	Lipids	Sulfur compounds	Fluorine compounds	Chlorine compounds	Silicon compounds	Plastics Metals Glass	Other non-organic material
BIOCHEMICAL CHEMICAL & PHYSICAL CONVERSION PROCESSES	Spontaneous anaerobic digestion in landfills	Engineered anaerobic digestion	Torrefaction 200 to 300 °C Anaerobic	Pyrolysis 500 to 700 °C Anaerobic	Gasification 800 to 2000 °C Limited Aerobic	Combustion (Incineration) 950 to 1100 °C Excess air	Hydrolysis, Fermentation & Distillation (for ethanol production)	Weak acid- and trans-esterification (for biodiesel production)	Thermo-catalytic reaction (for fuel synthesis)	Pre-treatment (cleaning) of gaseous products	Extraction and refining of liquid products	Pelletization	Co-firing with fossil fuels
INTERMEDIATE PRODUCTS	CH_4	CO_2	CO & H_2	Pyrolysis oil	Methanol	Ethanol	Biodiesel	Bio-oils (fuel grade vegetable oils	Synthetic gasoline & diesel	Refuse Derived Fuel (RDF)	Heat	H_2S, SO_2 & other trace gases	Liquid & solid residuals
ENERGY CONVERSION & RELATED TECHNOLOGIES	Spark or Compression ignition engine	Gas turbine	Micro (gas) turbine	Stirling engine	Fuel cell	Steam turbine	Steam boiler	Co- & tri-generation	Absorption & adsorption cooler	Binary Cycle (ORC) turbine, thermo-electric generator, thermoacoustic heat transformer, & other waste heat utilization technologies			Flue gas cleanup & residual treatment
FINAL PRODUCTS & SOME OF THE OUTCOMES	Electrical energy	Mechanical energy	Transport energy (Fuels)	Domestic & industrial heating	Domestic & industrial cooling	Organic fertilizers	Charcoal & other solid fuels	Speciality chemicals	Carbon credits	Generation of local job positions at all competency levels		Elimination of waste or minimization of the un-wanted impacts of waste on the environment	

Table 13: A Comparative Overview of some of the Thermal Biomass-to-Energy Technologies. Adapted after modifications from [26] and [27].

Comparison Criteria		Combustion with Energy Recovery	Pyrolysis	Gasification
Proven and reliable technology; Track record		Yes; Very common	Partly; Few	Partly; Few
Basic principle of treatment		Combustion with excess air, temperature 950~1100 °C	Anaerobic thermo-chemical conversion temperature 500-700 °C, retention time 0.5 ~ 1 hour	Aerobic thermo- chemical conversion temperature 800~2000 °C, retention time 0.5~1 hour
Plant complexity		Simple	Medium	Highly complex
Plant capacity		Large	Small	Small
Cost of treatment per tonne of waste		Medium to high	Medium to high	High to very high
Waste acceptance		All waste since air cleaning technology is good and residual solids are minimized by volume reduction	In particular suitable for contaminated, well defined dry waste fractions	Source separated dry waste only unless combined with better cleaning technology
Excluded waste fractions		None	Wet household waste	Wet household waste
Environmental Quality	Solids	Medium	Low	Medium - High
	Air	Medium – High	Medium - High	Medium - High
	Water	High	High	Medium - High
	Control of odor	Good	Good	Good
	Work environment	Good	Good	Good
Energy recovery		7,500-10,000 MJ per tonne of waste, CHP efficiency up to 85%	Approximately 70 % of combustion + energy containing product (char)	Approximately 50% of combustion
Carbon cycle (% of weight)		1 % in solids 99 % to air	20 - 30 % in solids rest to air	2 % in solids 98 % to air
Quality products for recycling (recovery, % weight of waste input)		15-20 % Bottom Ash (incl. Clinker, Grit, Glass) 3 % Metals	30 - 40% Char (incl. Bottom Ash, Clinker, Grit, Glass) 3 % Metals	15 - 25 % Bottom slag (incl. Clinker, Grit, Glass) 3 % Metals
Residuals for safe deposit or after-treatment (% weight of waste input)		Post-combustion fly ash & flue gas residues 2 - 3 %	Post-combustion flue gas residues 2-3%	Pre-combustion gas cleaning residues 2 %

Estimated Levelized Cost of New Generation Resources, 2016.

Plant Type	Capacity Factor (%)	U.S. Average Levelized Costs (2008 $/megawatthour) for Plants Entering Service in 2016				
		Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System Levelized Cost
Conventional Coal	85	69.2	3.8	23.9	3.6	100.4
Advanced Coal	85	81.2	5.3	20.4	3.6	110.5
Advanced Coal with CCS	85	92.6	6.3	26.4	3.9	129.3
Natural Gas-fired						
Conventional Combined Cycle	87	22.9	1.7	54.9	3.6	83.1
Advanced Combined Cycle	87	22.4	1.6	51.7	3.6	79.3
Advanced CC with CCS	87	43.8	2.7	63.0	3.8	113.3
Conventional Combustion Turbine	30	41.1	4.7	82.9	10.8	139.5
Advanced Combustion Turbine	30	38.5	4.1	70.0	10.8	123.5
Advanced Nuclear	90	94.9	11.7	9.4	3.0	119.0
Wind	34.4	130.5	10.4	0.0	8.4	149.3
Wind – Offshore	39.3	159.9	23.8	0.0	7.4	191.1
Solar PV	21.7	376.8	6.4	0.0	13.0	396.1
Solar Thermal	31.2	224.4	21.8	0.0	10.4	256.6
Geothermal	90	88.0	22.9	0.0	4.8	115.7
Biomass	83	73.3	9.1	24.9	3.8	111.0
Hydro	51.4	103.7	3.5	7.1	5.7	119.9

Source: Energy Information Administration, Annual Energy Outlook 2010, December 2009, DOE/EIA-0383(2009)

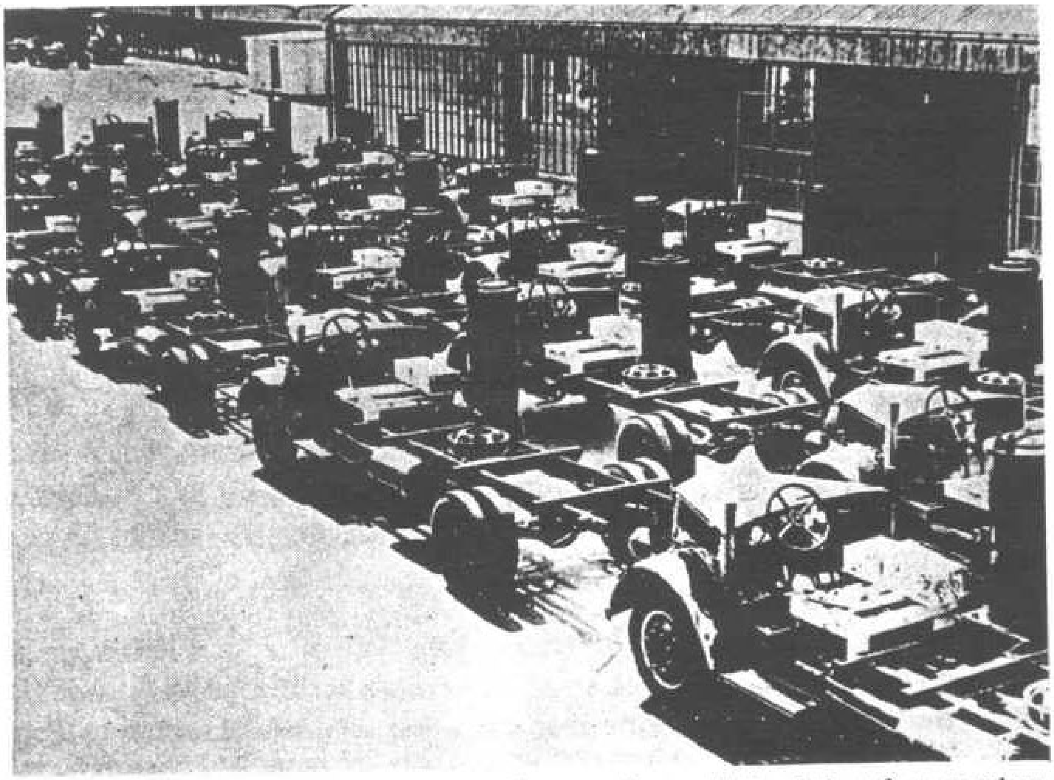
Figure 2. Estimated levelized cost of new generation energy resources. Adapted from [23].
Abbreviations: O&M = operation and maintenance, CC = combined cycle, CCS = carbon control and sequestration, PV=photovoltaics, GHG = greenhouse gas.

Figure 7. A covered lagoon digester [51].

Figure 8. A Fixed film digester [50].

Figure 9. A complete mix digester [52].

Figure 10. A Plug-flow digester [50]



Germany, about 1943. Mass production of gas producer vehicles, Imbert factory, where some 500,000 gas producers were manufactured during World War II. (E. E. Donath)

Figure 12a. Mass produced wood gas powered vehicles with completed chassis, waiting for body works [53]. The wood gas generator is the dark colored cylinder on the right hand side of the vehicle.

Figure 12b. This Volvo 240 reaches a maximum speed of 120 kilometers per hour and can maintain a cruising speed of 110 km/h. The "fuel tank" can contain 30 kilograms of wood, good for a range of 100 kilometers, comparable to that of a 2010 model electric car. [60]

14. References

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APPENDIX A

EVALUATION OF THE COMPARISON CRITERIA IN TABLE 7 FOR VARIOUS RENEWABLE ENERGY CONVERSION TYPES

Data sources:[15], [21], [66], [67], [68], [69], [70], [71], [72], [73]

ENVIRONMENTAL FRIENDLINESS (MINIMUM HARM)

Type of Renewable Energy	Grade	Comments
Solar Concentrated PV	5	No significant environmental harm
Solar Photo-voltaic	5	No significant environmental harm
Biomass Small Scale	5	No significant environmental harm
Solar Thermal Electric	4	Cooling water use, low level noise
Biomass Large Scale	4	Flue gas and solid residue pollution potential
Enhanced Geothermal	4	Water consumption, un-reinjectable brine
Hydro-Geothermal	4	Non reinjectable brine
Hydro small scale, run-of-the-river	4	Diversion of irrigation water resources
Wind	4	Noise, some bird loss
Tidal	3	Wild life is displaced from their regular habitat on the shore, hindrance to sea navigation,
Wave	3	Disturbances in the sea-floor and to marine ecosystems, accidental hydraulic fluid leaks to the sea, noise pollution, hindrance to sea navigation
Hydro large scale with dam	2	Large cultivatable land area occupation, possible human settlement relocation and wildlife habitat destruction, other changes in the close environment, possibility of a very big flood if the dam wall fails

POSITIVE CONTRIBUTION TO THE ENVIRONMENT

Type of Renewable Energy	Grade	Comments
Biomass Small Scale	5	Elimination of waste or minimization of Elimination of waste or minimization of the unwanted impacts of waste on the environment
Biomass Large Scale	5	Elimination of waste or minimization of Elimination of waste or minimization of the unwanted impacts of waste on the environment
Hydro large scale with dam	4	Provision of large scale irrigation, prevention of floods, recreational contribution
Enhanced Geothermal	0	No significant environmental gain
Hydro-Geothermal	0	No significant environmental gain
Hydro small scale, run-of-the-river	0	No significant environmental gain
Tidal	0	No significant environmental gain
Wind	0	No significant environmental gain
Solar Concentrated PV	0	No significant environmental gain
Solar Photo-voltaic	0	No significant environmental gain
Solar Thermal Electric	0	No significant environmental gain
Wave	0	No significant environmental gain

WORLDWIDE AVAILABILITY

Type of Renewable Energy	Grade	Comments
Biomass Small Scale	5	Worldwide generation of biomass in almost all forms
Biomass Large Scale	5	Worldwide generation of biomass in almost all forms
Solar Concentrated PV	4	Worldwide availability of sun shine with usable intensity up to the latitudes of North Germany
Solar Photo-voltaic	4	Worldwide availability of sun shine with usable intensity up to and including the latitudes of northern Germany
Solar Thermal Electric	4	Worldwide availability of sun shine with usable intensity up to and including the latitudes of northern Germany
Enhanced Geothermal	3	Available worldwide, but limited by the cost of very deep well drilling
Hydro small scale, run-of-the-river	3	Available in most regions of the world except arid zones
Wind	3	Available in most regions of the world, and in off-shore locations
Hydro large scale with dam	2	Limited availability in certain regions of the world
Wave	2	Limited availability in regions with access to open sea
Hydro-Geothermal	1	Limited availability in only few regions in the world
Tidal	1	Limited availability in only few regions in the world

AVAILABILITY CLOSE TO POINTS OF USE		
Type of Renewable Energy	**Grade**	**Comments**
Solar Concentrated PV	5	Solar energy is the most distributed renewable energy on earth
Solar Photo-voltaic	5	Solar energy is the most distributed renewable energy on earth
Biomass Small Scale	5	Small scale biomass is available at the household level
Biomass Large Scale	4	Biomass is widely distributed, but some energy transmission is needed since it is feasible in larger systems
Solar Thermal Electric	4	Some energy transmission is needed since it is feasible especially in larger systems
Hydro small scale, run-of-the-river	3	Medium scale hydro energy is widely available in suitable regions
Wind	2	Long range energy transmission is needed since it is available in selected areas and feasible only in larger systems
Wave	2	Potential to serve all locations near to the open sea coast in a distributed way, but available only in coastal areas
Enhanced Geothermal	2	Long range energy transmission is needed since it would be available in selected areas and feasible only in larger systems
Hydro-Geothermal	1	Long range energy transmission is needed since it is available in only few locations and feasible only in larger systems
Hydro large scale with dam	1	Very long range energy transmission is needed since it is feasible only in very large systems
Tidal	1	Long range energy transmission is needed since it is available in only few locations and feasible only in larger systems

PLANT SIZE SCALABILITY		
Type of Renewable Energy	**Grade**	**Comments**
Solar Photo-voltaic	5	mW to MW scale
Solar Concentrated PV	4	W to MW scale
Wind	4	W to MW scale
Solar Thermal Electric	3	kW to MW scale
Hydro small scale, run-of-the-river	3	kW to MW scale
Biomass Large Scale	3	Upper kW to MW scale
Hydro large scale with dam	2	Upper MW to GW scale
Biomass Small Scale	2	kW ~ 10 kW scale
Hydro-Geothermal	1	MW scale only
Wave	1	MW scale only
Tidal	1	MW scale only
Enhanced Geothermal	1	Upper MW scale only

CURRENT TECHNOLOGICAL CAPABILITY		
Type of Renewable Energy	**Grade**	**Comments**
Biomass Small Scale	5	A total of 29 million units are reported to be operating in China and India
Hydro large scale with dam	5	Well established technology
Hydro small scale, run-of-the-river	5	Well established technology
Hydro-Geothermal	4	Fairly proven technology
Wind	4	Fairly proven technology
Biomass Large Scale	3	Proven technology in some conversion types
Solar Photo-voltaic	3	Proven silicon based technology, but concerns over material availability
Solar Concentrated PV	2	At the commercialization stage and concerns over material availability
Solar Thermal Electric	2	At the commercialization stage
Enhanced Geothermal	1	Yet under development and testing in few locations in MW scale
Wave	1	Yet under development and testing in few locations in MW scale
Tidal	1	Yet under development and testing in few locations in MW scale

POTENTIAL FOR TECHNOLOGY IMPROVEMENT		
Type of Renewable Energy	**Grade**	**Comments**
Solar Photo-voltaic	5	Major budgets allocated for developing better technologies
Solar Concentrated PV	5	Major budgets allocated for developing better technologies
Solar Thermal Electric	4	Modest budgets allocated for developing better technologies
Wind	4	Ongoing development efforts by major companies
Biomass Large Scale	3	Ongoing development efforts by many companies
Enhanced Geothermal	3	New technology under development by major countries
Wave	2	New technology under development by few companies
Tidal	2	New technology under development by few companies
Biomass Small Scale	1	Currently stabilized technology implementable with very limited resources
Hydro-Geothermal	1	Currently stabilized technology
Hydro large scale with dam	1	Currently stabilized technology
Hydro small scale, run-of-the-river	1	Currently stabilized technology

CAPACITY FACTOR		
Type of Renewable Energy	**Grade**	**Comments**
Enhanced Geothermal	5	~ % 90
Hydro-Geothermal	5	~ % 90
Biomass Large Scale	4	~ % 85
Biomass Small Scale	4	~ % 75
Hydro large scale with dam	3	~ % 50
Wind	2	~ % 30
Solar Concentrated PV	2	~ % 30
Solar Thermal Electric	2	~ % 30
Hydro small scale, run-of-the-river	1	% 20 ~ 35
Tidal	1	% 20 ~ 35
Solar Photo-voltaic	1	% 20
Wave	1	% 15 ~ 30

UNPREDICTABLE SOURCE VARIABILITY (Grade assigned inversely proportional)		
Type of Renewable Energy	**Grade**	**Comments**
Tidal	5	Highly Predictable
Enhanced Geothermal	5	Highly Predictable
Hydro-Geothermal	5	Highly Predictable
Biomass Small Scale	5	Predictable as long as household or farm functions
Biomass Large Scale	4	Yearly harvest unpredictability in case of energy crops, otherwise predictable
Hydro large scale with dam	3	Yearly rain unpredictability
Solar Concentrated PV	3	Cloudy day unpredictability except in deserts
Solar Photo-voltaic	3	Cloudy day unpredictability except in deserts
Solar Thermal Electric	3	Cloudy day unpredictability except in deserts
Hydro small scale, run-of-the-river	1	Short term (~ monthly) rain unpredictability
Wind	1	Short term (daily ~ monthly) wind unpredictability
Wave	1	Short term (daily ~ monthly) wind unpredictability

LAND AREA OCCUPATION (Grade assigned inversely proportional)		
Type of Renewable Energy	**Grade**	**Comments** (Note: Power transmission lines area occupation not considered)
Wind	5	0.1 m2 per kW
Wave	5	Very small land area occupation per kW
Tidal	4	Small land area occupation per kW
Enhanced Geothermal	3	~ 0.5 m2 per kW
Hydro-Geothermal	3	~ 0.5 m2 per kW
Hydro small scale, run-of-the-river	3	~ 1 m2 per kW except the area for piping from the water source to the turbine
Biomass Large Scale	3	~ 2 ~ 10 m2 per kW, depending on conversion method
Biomass Small Scale	3	~ 5 ~ 10 m2 per kW, decreasing with higher powers
Solar Concentrated PV	2	Proportional to power rating, approximately 10 m2 per kW
Solar Photo-voltaic	2	Proportional to power rating, approximately 10 m2 per kW
Solar Thermal Electric	2	Proportional to power rating, approximately 10 m2 per kW
Hydro large scale with dam	1	Very large land area occupation

IMPLEMENTATION TECHNOLOGY LEVEL (Grade assigned inversely proportional)		
Type of Renewable Energy	**Grade**	**Comments**
Biomass Small Scale	5	Very low
Solar Photo-voltaic (PV)	4	Low
Solar Concentrated	3	Medium
Solar Thermal Electric	3	Medium
Biomass Large Scale	3	Medium
Hydro small scale, run-of-the-river	3	Medium
Wind	3	Medium
Hydro-Geothermal	2	High
Wave	2	High
Tidal	2	High
Enhanced Geothermal	1	Very High
Hydro large scale with dam	1	Very high

PROJECT IMPLEMENTATION TIME (*)		
Type of Renewable Energy	**Grade**	**Comments**
Solar Photo-voltaic (PV)	5	Hours ~ days
Biomass Small Scale	4	Days ~ Month
Solar Concentrated PV	3	~ Months
Solar Thermal Electric	3	~ Year
Biomass Large Scale	3	~ Year
Hydro small scale, run-of-the-river	3	~ Year
Wind	3	~ Year
Hydro-Geothermal	2	5 ~ 7 years
Hydro large scale with dam	2	5 + years
Wave	1	Not ready for wide scale implementation
Tidal	1	Not ready for implementation
Enhanced Geothermal	1	Not ready for implementation

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