

EFFICIENCIES OF CONVERSION PATHS FOR RENEWABLES

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ABSTRACT

Several capture and conversion processes are analyzed to determine the range and likelihood of their efficiencies. The efficiencies are related to the surface area per kW required by the capture technology (electric or thermal) of end use utility. It is found that not all the polygeneration processes considered result in the smaller area requirements, and that the area requirements to provide mechanical power are comparatively large. However, the smallest area results for industrial absorption heating/refrigeration in polygeneration configurations.

INTRODUCTION

Polygeneration is an established way to save fossil fuels. The integration of power and thermal demands results in reduced fossil fuel inputs over those required to meet the same needs separately. Renewables propose a different economy: the cost of renewable energy is null, but its low density and transient nature require comparatively expensive capture and storage technology to meet the needs of the societies with high-living standards. It is indeed intriguing to address the benefits of polygeneration for renewables, because the efficiency of harvesting and storing the energy could be enhanced if the supplies and demands are integrated. A simple energetic analysis of some, not all, possible conversion paths is presented here, on the basis that sustainability calls for energy previous to economic viability.

The resource and possible outcomes

The Sun is a fusion reactor conveniently distanced from the Earth. The incoming solar energy has the highest possible thermodynamic quality: its exergy corresponds to infinite temperature, i.e. its convertibility into other forms is not limited by the Second Law of Thermodynamics. This is not to say that direct conversion does not have its limits, which it does, but at least in theory Carnot efficiency limitations do not apply to all the conversion paths. Consider then, the conversion possibilities for the yearly average solar energy arriving to 1 m² of surface in the Midwest of the USA, typically 5 kwe·hr/day (the ending e in kwe is used to indicate that the full amount striking the surface could be converted into electric power) . These 5 kwe·hr/ m²·day are equivalent to 1.12 bre/yr of oil, which we approximate as 1 bre/yr.

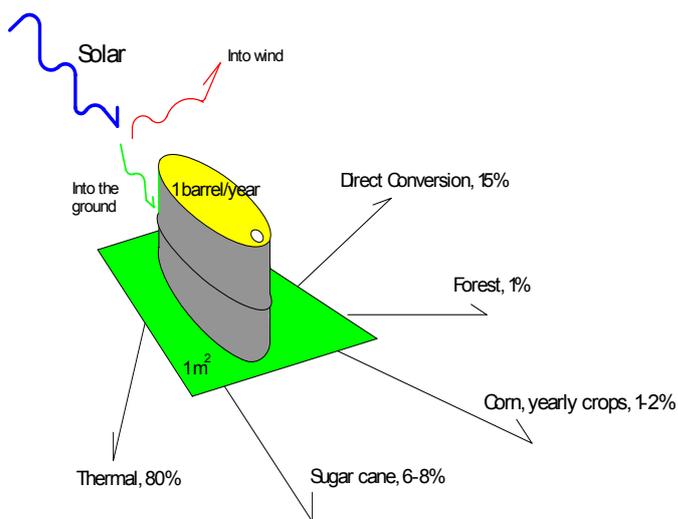


Figure 1. One barrel can be used in many ways.

Conversion possibilities of the yearly barrel are now discussed. Of the incoming energy, a certain fraction will heat the ground and the air and result in convective currents that generate wind. For the fraction that strikes the surface, the conversion possibilities are many, and we outline but a few in Fig 1. The conversion to thermal can

have high efficiencies, depending on the conversion and ambient temperature, and its upper limit is 100 %. The direct conversion to electrical energy can have a wide efficiency range, from the peak of 40% achieved with sophisticated solar cells, to values from 5 to 20% with inexpensive cells. A value of 15 % is typical. Finally, solar

energy can be captured by biomass, with energy efficiencies (stored energy to energy input) ranging from 1 % to 6%, depending on the crop.

The magnitude of the solar resource for thermal and direct conversion is quite large, as is also the wind resource. An idea of the magnitude of the thermal resource for the world and for the USA can be gained by inspection of Fig 2. For the world, collection and storage of only 5% of the incoming resource would more than suffice to meet current thermal energy demands. In the case of the USA, the same situation applies. Solar thermal is plentiful on average, although its extensive use poses financial challenges where fossil fuels are inexpensive.

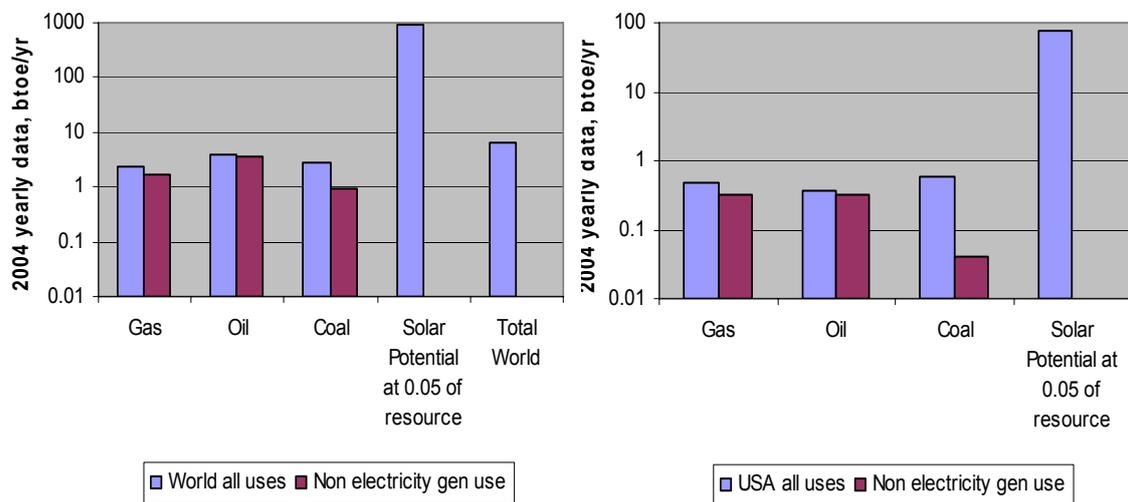


Figure 2. Production for all uses and excluding power generation, for the world and USA. Solar thermal potential estimated at 0.05 of solar energy arriving to the land mass in one year.

The case for direct conversion to electricity via photovoltaic is clear in terms of resources, Fig 3. The yearly production rates from different sources are dwarfed by the photovoltaic potential even for a small assumed efficiency of 2%. This is the case both for the World and for the USA.

POLYGENERATION AT THE SOURCE

The literature on renewables, rich in many ways, is not prodigal regarding cogeneration at the source. Yet, in the right circumstances, integration of electrical and thermal production can reduce surface area utilization. The premise is that because conversion to electricity is never 100% efficient the waste heat appearing can be delivered as process or space heat, Fig 4. In this figure, the incoming radiation is captured, and what cannot be converted to power is (if possible) used as waste heat.

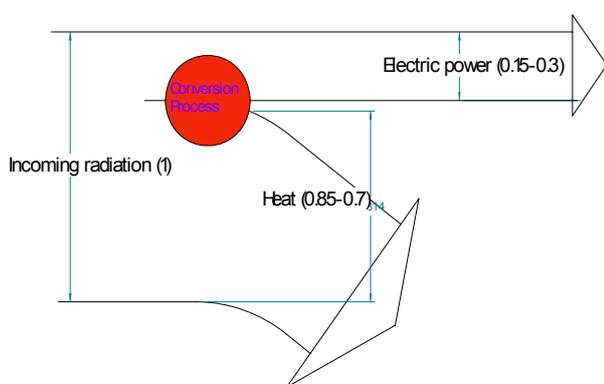


Figure 4. polygeneration at capture

The most common application of the ideas suggested by Fig 4 is the cooling of Si cells in concentrating [1] or even non-concentrating situations. In economies that favor concentration of solar radiation via parabolic mirrors (i.e. if mirror surface is cheaper than solar cell surface), cooling of the cells is required. Use of the ensuing waste heat may be

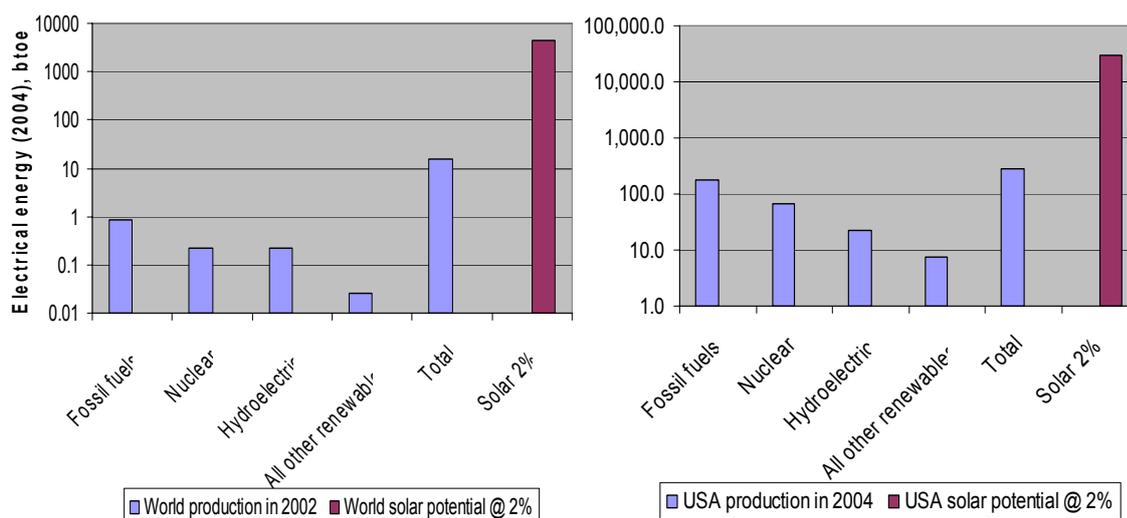


Figure 3. Recent electrical energy production and comparison to 2% of solar resource

justified. A plant along these lines of thought had been tested previously [2]. An interesting application of this concept does not involve solar energy, but radiant energy from sources on Earth, such as flames. The concept uses low bandgap photovoltaic cells to generate power from flames. Because the combustion products are used for process heat, the proposed systems [3] are projected to have large efficiencies. In any case, if the waste heat is available, power generation should be fostered as a general rule.

ESTIMATION OF CONVERSION EFFICIENCIES

All thermal devices have a design efficiency, which normally is high, for the expectation is that the device will operate most of the time at design. Efficiencies tend to fall off from design due to various factors. For instance, photovoltaic cells (PV cells) have nominal efficiencies (defined as electric output divided by energy input) that can be quite high. Yet, the angle of incidence of the incoming radiation, the cell temperature, the irradiance, the electrical resistance and other factors [4, 5] considerable influence the efficiency. As components age, their efficiency tends to deteriorate. Part load operation is typically less efficient than full load for most conversion devices. Poor or lack of maintenance translates into lower efficiencies. When evaluating the conversion efficiency of a chain involving different technologies, it is important to ascertain the values of the most likely efficiency, because R&D and business decisions call for educated guesses about the future.

How can then many unpredictable circumstances and decisions be factored in an evaluation of efficiency? The problem is not intractable, but it cannot be solved precisely. Whatever solution is produced concerning the future carries a certain amount of subjectivity, except in exceptional circumstances or concerning exceptional beings.. “Life is a series of collisions with the future; ...” (Ortega y Gasset) and those collisions are unpredictable. We propose here to deal with these uncertainties via estimates based on probability.

Until more information is available, two probability distributions are adopted. One is selected for the flexibility that it exhibits representing skewed distributions. Of long standing in reflecting the probability of equipment lifetime, we adopt it here for its flexibility, not for its relationship to service life. Mathematically, the Weibull distribution can be casted as

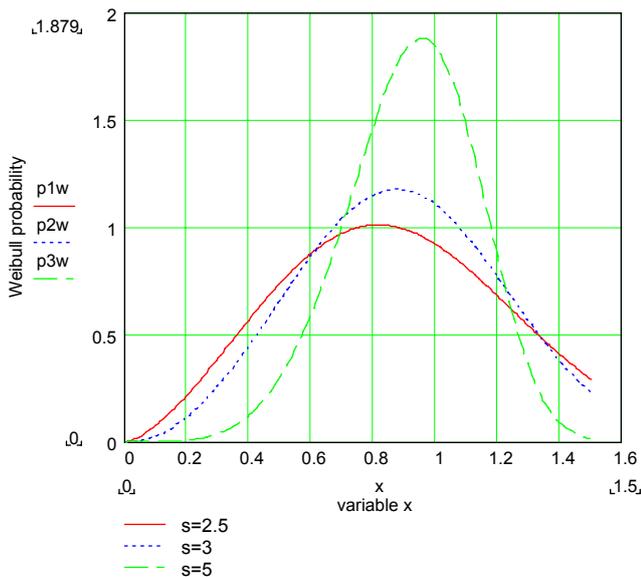


Figure 5. Weibull distributions for varying s

$$P(x) = s \cdot x^{s-1} \exp(-x^s) \quad (1)$$

The parameter s determines the shape of the distribution. For each value of x there corresponds a value $p_w(x)$, which can be regarded as the relative probability of x for a given s, as shown in Fig 5.

We adopt here the distribution corresponding to $s=2.5$. With an estimate of maximum and minimum efficiency for a certain technology, a change of independent variable yields the desired probability distribution. For instance, for PV cells with inverter and storage system current efficiencies are adopted as

$$\eta_{\max} = 0.2, \quad \eta_{\min} = 0.1$$

and if UL and LL denote the upper and lower values of x, the following transformation (Eq 2) yields the Weibull distribution for efficiency values.

$$\eta_w = (x - LL) \cdot \frac{(\eta_{\max} - \eta_{\min})}{UL - LL} + \eta_{\min} \quad (2)$$

The distribution of thus obtained affords the following interpretation: a number of PV systems will reach a high efficiency of 20%. In a market with multiple entries,

the probability of encountering such system would be 0.3. An efficiency of 15% would be found 3.3 times more frequently, for its (non normalized) probability is about 1. Finally, the probability of finding a system with combined efficiency of 10% is null, meaning that such low efficiency would be detected and eliminated from the market.

A similar interpretation applies to the other probability distribution adopted here, the Gaussian probability density distribution. The symmetric distribution has a standard deviation of 1.6. Typically, we apply this density to distribution networks and equipment that is maintained to meet clear standards. When the mean value of efficiency is well known, this distribution is adopted. Then, consider a sequence of two energy conversions, labeled transformations in Fig 6. Transformation I receives energy input $E_{I_{in}}$ from a source, and delivers an output $E_{I_{out}}$. This output serves as input to process II, which delivers a useful output $E_{II_{out}}$. The efficiencies of each transformation are given by as η_I and η_{II} . It is clear that the combined efficiency η_0 will be the product of the efficiencies of each intervening process. If we accept that each efficiency will depend on a number of unpredictable factors, but that a probability distribution for each efficiency exist, then we can sample each distribution (one for process I, one for process II) randomly and produce the probability of each random combination of efficiencies by multiplying each probability. As this process is repeated for the full range of efficiencies, a distribution of the efficiencies of the process emerges, such as the one shown in Fig 7. In this figure, the combined probability is shown as function of indexes identifying the efficiencies of processes I and II. The peak probability corresponds to product of efficiencies that is, under the assumed conditions, most likely to occur.

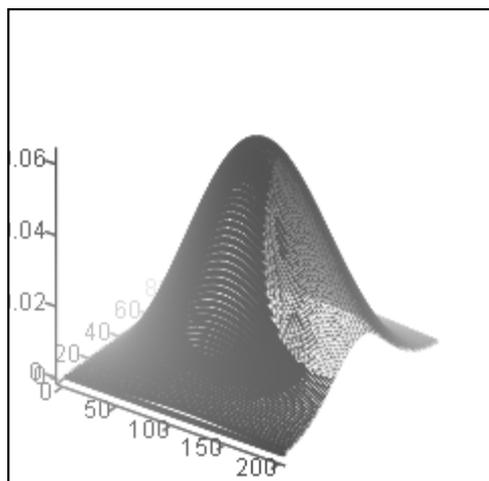


Figure 7. Sequential process probability distribution

We apply this procedure to the sequences of energy conversion that are currently possible, to ascertain their potential. Processes after capturing the renewable energy are susceptible to this analysis.

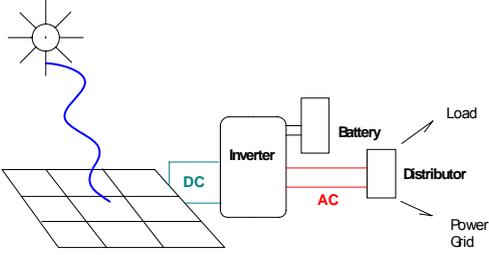
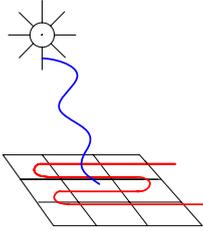
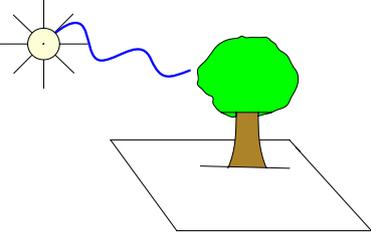
GENERATION AND POLYGENERATION AFTER CAPTURE

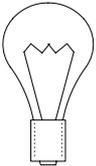
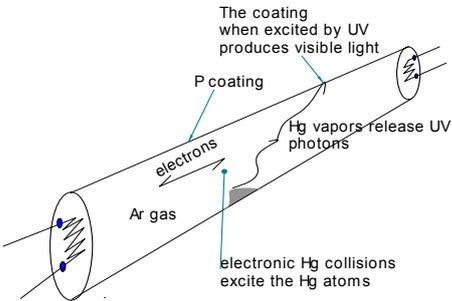
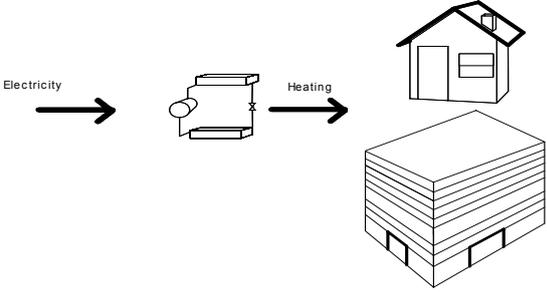
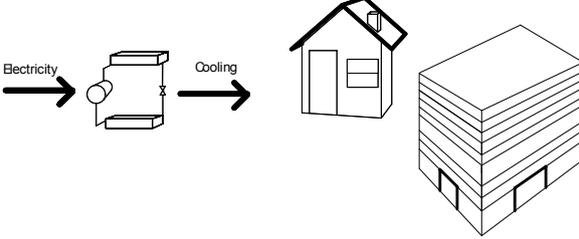
Schemes to use thermal or electrical energy abound in every place. The ultimate viability of renewable resources will hinge on their impact on relieving depletable energy sources using a minimum of surface area. We select here a number of processes, some applying polygeneration or alternative technology to establish their energy and surface area fitness. The intent is to reduce area and energy requirements, thus reducing the initial capital outlay required by renewables.

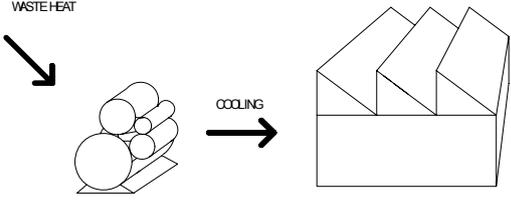
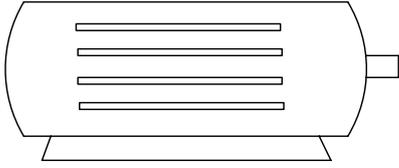
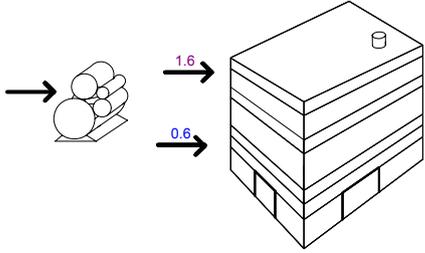
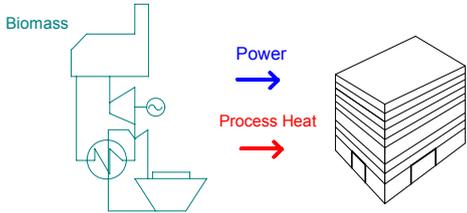
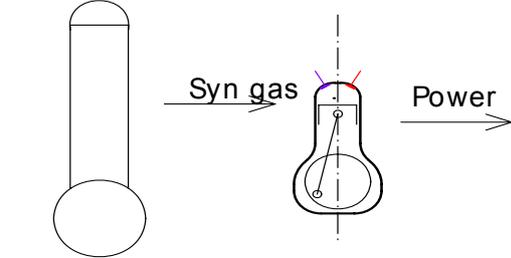
The capture processes are outlined in Table 1, and end use technology in Table 2. For distribution of electric power via a conventional grid we use as guideline the value of the EIA, namely $\eta=0.91$, and adopt $\eta_{\max}=0.93$ and $\eta_{\min}=0.88$. For thermal storage $\eta_{\max}=0.93$ and $\eta_{\min}=0.88$ were adopted. Processes are obtained combining the elements of each table in a proper sequence. Each process is assigned a letter (c, d, st, and u for capture, distribution, storage (thermal) and end use respectively), and a number that identifies its position in each table. As the processes are combined with reference to Fig 6 above, the most likely efficiency is

reported in Table 3, which also contains information regarding the probability density distributions assumed for analysis.

Table 1. Capture of renewables

| | | |
|--|---|--|
| <p>C1. Sun to PV power to batteries to load/grid</p> |  | <p>$\eta_{\max}=0.2$ $\eta_{\min}=0.1$</p> |
| <p>C2. Sun to hot water/fluid</p> |  | <p>$\eta_{\max}=0.85$ $\eta_{\min}=0.6$</p> |
| <p>C3. Biomass</p> |  | <p>$\eta_{\min}=0.005$ [6] $\eta_{\max}=0.03$ [6] Release of O₂: priceless.</p> |

| Table 2 END USE TECHNOLOGIES CONSIDERED | | |
|---|--|-------------------------|
| U1: Incandescent |  | <p>0.07</p> <p>0.05</p> |
| U2: Fluorescent |  | <p>0.24</p> <p>0.3</p> |
| U3. Power to Heat, heat pump |  | <p>5</p> <p>1.2</p> |
| U4. Power to cooling. Electric chiller |  | <p>5.5</p> <p>2</p> |

| | | |
|---|--|---|
| <p>U6. Single effect absorption chiller</p> |  | <p>0.6</p> |
| <p>U5. Power to Power, electric motor</p> |  | <p>0.95 (large and optimized) 0.5 (small and inexpensive)</p> |
| <p>U7. Absorption refrigeration and heating in polygeneration</p> |  | <p>Heating 1.4-1.6 Cooling 0.5-0.6</p> |
| <p>U8. Combined power/process heat</p> |  | <p>0.33 Thermal 0.30 Thermal 0.28 Biomass [6]</p> |
| <p>U9. Biomass to Syngas to mechanical power/H2</p> |  | <p>To H2: 48% (0.46-0.50) To Power: 31.4% (0.28-0.33) [7]</p> |

DISCUSSION

Solar and lighting

The first entry in Table 3 (. C1-D1-U1) concerns solar capture to power (C1), then to distribution (D1) via a conventional network, and to end use (U1). The assumed distributions for efficiency were Weibull, Gaussian and Gaussian respectively, indicated as WGG in the table. The energy efficiency of this sequence is small, in the order of 0.009. The area requirement is calculated for an average solar power input of 5 kw·hr/m²·day, to generate 100 lumen (A 100 W incandescent puts out about 1700-1300 lumen). The efficiency of PV power injected in the net and used with incandescent bulbs is 3.7 m²/100 lumen. Entry 2 (C1-D1-U2) reflects similar calculations for fluorescent lights instead, resulting in area requirement of 0.14 m²/100 lumen. Given the importance of lighting to the human endeavor, fluorescents or other efficient lighting seem of great promise for use in conjunction with photovoltaic technology.

| Table 3. RESULTS SUMMARY | | |
|--------------------------|--|---|
| Sequence | Efficiency and area requirement | Remarks (Distributions) |
| 1. C1-D1-U1 | $\eta_1=0.009$ $\eta_{Area}=3.7 \text{ m}^2/100\text{lm}$ | PV to distribution net to incandescent light (WGG) |
| 2. C1-D1-U2 | $\eta_1=0.04$ $\eta_{Area}=0.14 \text{ m}^2/100\text{lm}$ | PV to distribution net to fluorescent light (WGG) |

| | | |
|-------------|--|---|
| 3. C1-D1-U3 | $\eta_1=0.53$ $\eta_{Area}=9 \text{ m}^2/\text{kWth}$ | PV to distribution to heat pump. (WGW) |
| 4. C1-D1-U4 | $\eta_1=0.44$ $\eta_{Area}=11 \text{ m}^2/\text{kWth}$ | PV to distribution to chiller (WGW) |
| 5. C2-D2-U6 | $\eta_1=0.38$ $\eta_{Area}=12 \text{ m}^2/\text{kWth}$ | Solar thermal, storage, absorption chiller (WGW) |
| 6. C1-D1-U5 | $\eta_1=0.1$ $\eta_{Area}=47 \text{ m}^2/\text{kWe}$ | PV to distribution to electric motor (WGW) |
| 7. C2-D2-U7 | $\eta_1=1.47$ provided load is balanced $\eta_{Area}=3.2 \text{ m}^2/\text{kWth}$ | Solar thermal, heating and cooling (WGW) |
| 8. C3-U8 | $\eta_1=0.012$ $\eta_{Area}=596 \text{ m}^2/\text{kWe}$ $\eta_{Area}=199 \text{ m}^2/\text{kWth}$ $\text{kWe}=3\text{kWth}$ | Biomass, combined power and heat. (WWW) |
| 9. C3 -U9 | $\eta_1=0.018$ $\eta_{Area}=401 \text{ m}^2/\text{kWe}$ $\eta_{Area}=133 \text{ m}^2/\text{kWth}$ $\text{kWe}=3\text{kWth}$ | Biomass, gasification to power or H ₂ (WWW) |

Space conditioning with advanced electric or absorption chillers

Space conditioning is another application much sought, especially heating. Variable speed compressors and fans entail high equipment efficiencies, specially when the temperature differences between the outdoors and the conditioned space are smaller than during design. The sequence PV-network-heat pump (third entry, C1-D1-U3) has an area requirement (for 5 kw·hr/m²·day) of 9 m²/kWth. Cooling technologies with either vapor compression (4. C1-D1-U4) or absorption in conjunction with thermal storage (5. C2-D2-U5) require 11 and 12 m²/kWth respectively. A distinction must be drawn here. Whereas the required collector areas are similar, the cost of PV cells is much higher than that of thermal collectors. In any case, the fact that area requirements are similar seems like a good promise for both technologies when used with solar energy.

Mechanical power

Many applications in all energy consuming sectors require mechanical power. From elevators to presses or countless appliances, electric motors deliver mechanical power everywhere. Sequence 6 (C1-D1-U6) evaluates the efficiency of this application. The uncertainties of the method employed for this work are manifest here, for the adopted Weibull distribution may not describe the efficiency distribution of electric motors well. There are many more small motors than large ones, hence the probability of low efficiencies should be large. However, if large motors consumed most of the power, then the probabilities of large efficiencies would materialize. The distribution of Fig 2 for $s=2.5$ supports the latter scenario. Under the assumed conditions, then, the overall sequence most likely efficiency is 10 %, with an area requirement of 47 m²/kWe. This is a large area, because the efficiency of electric motors is not as large as the thermal efficiency of heat pumps. In practical terms, solar PV proposes a more efficient area utilization for space conditioning than for raw mechanical power.

Polygeneration and solar energy

Just as is the case with fossil fuels, polygeneration is warranted where all outputs can be used. In the case of solar thermal capture activating an absorption machine designed to deliver low-temperature process heat and cooling (7. C2-D2-U7), the area requirement is quite small: $3.2 \text{ m}^2/\text{kWth}$. To arrive at this requirement, the efficiency distributions for heating and cooling were assumed independent, but the allowed ranges were casted as to satisfy the constraints of known absorption designs. The benefits of cogeneration are apparent in this application. Such machines have been developed and a number of them have been installed, driven by natural gas, in settings requiring refrigeration and heating. The same technology could be driven with concentrating collectors. A recent review of the technology was offered in [8].

The use of traditional thermal cycles for polygeneration from biomass was considered in entry 8, C3-U8. In this application, biomass is burned in a suitable boiler to produce steam. Via an extraction turbine, power and process heat are produced simultaneously. An equivalence of 3 kWth to 1 kWe was assumed to evaluate area requirements in the present studies. Due to the low efficiency of photosynthesis, the area requirements are large. Of course, the area is in this case land, which tends to be cheaper than solar collectors in rural areas, but those areas seldom have uses for polygeneration products. In any case, the area requirement for electric power would fall in the $600 \text{ m}^2/\text{kWe}$, or in the $200 \text{ m}^2/\text{kWth}$ for thermal outputs. Currently, only when biomass refuse from food production is available does this type of cogeneration make sense [9].

The biomass, gasification to and use of (or storage) of hydrogen (last entry, C3-U9) also appears onerous in terms of area, although the storage capability ought to be of great value. The thermal requirements for the storage application are in the order of $133 \text{ m}^2/\text{kWth}$.

CONCLUSION

Polygeneration from renewables is most efficient when thermal energy is captured and delivered as process and refrigeration energy, given by sequence 7 in Table 3. This sequence implies a concentrating (or could be flat plate in some localities) solar collector and a specially designed single effect absorption heat pump. Biomass can be used for polygeneration as well, but the area efficiency tends to be low, and urban concentrations may not be able to profit from some of the technology advances due to the need to transport the biomass fuel from rural to urban areas. Hence, in the long term, biomass refuse may be more suited than energy plantations for power and heat generation.

A trait that consistently comes through when considering lighting or space conditioning, is that renewables will profit greatly in terms of initial capture investment from advances in energy efficient technology. Fluorescent lights and advanced heat pumps can make a strong difference as to how efficiently the energy captured is used. The large area requirements to provide mechanical power via electric motors does not augur well for renewables in this application. Clearly, the synergy afforded by some polygeneration schemes suggested here may result in a more energetic and hence financially rewarding scenario for new ventures.

ACKNOWLEDGEMENT

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