Chapter 2
Are Biofuels the Best Use of Sunlight?

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Abstract Biofuels are liquid sunlight. In effect, we use plants to convert raw solar energy into a liquid (ethanol or biodiesel) that can be used as an energy source for our transportation systems. The question this chapter asks is whether this conversion process is the best way to make use of solar energy. Photovoltaics clearly dominate plants in terms of technical conversion efficiency, with conversion rates for commercial cells of the mid-2000s that are 2–10 times higher than plants and operate throughout the year rather than just during the growing season. But photovoltaics provide electricity, which is not currently cost-effective for use in transportation. As research into photovoltaics and battery technology is still in its infancy, the potential for commercially viable technology breakthroughs seems high.

2.1 Introduction

Biofuels are liquid sunlight. In effect, we use plants to convert raw solar energy into a liquid (ethanol or biodiesel) that can be used as an energy source for our transportation systems. The question this chapter asks is whether this conversion process is the best way to make use of solar energy. The answer to this question has three parts – what is the technical efficiency of the conversion process from solar power to useful energy relative to other methods of transforming solar power, to what extent are the resulting products substitutable, and what are the fixed and operating costs of the conversion process? This chapter compares biofuels with the most widely used alternate conversion process – photovoltaics.

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Plants capture the energy of the sun through photosynthesis and transform it to starches, sugars, and cellulose. Liquid biofuels are created with various industrial processes that combine the plant material with additional energy and water and produce a biofuel and byproducts, including polluted water. The output, either ethanol or biodiesel, can relatively easily be used in the world's transportation systems.

Much attention has been paid to whether the energy used in the industrial processes that produce ethanol is greater or less than the energy available in the final product, and whether that energy is derived from fossil fuels or renewable sources such as bagasse. Farrell et al. (2006) found that ethanol produced with today's conversion technology required 0.774 MJ of direct and indirect fossil fuel inputs to produce 1.0 MJ of fuel (Summary table of Farrell et al., at http://rael.berkeley.edu/ebamm) for a net energy yield (NEY) of 1.30. Liska et al. (2009) argue that the Farell et al. results are based on older technology and find NEYs of 1.29–2.23 depending on feedstock for the conversion process and corn yields (see Table 2.1 below). However, little attention has been paid to the efficiency of converting the underlying energy source – solar – to a form directly useful to humans.

Table 2.1 The annual energy output of various biofuels

	Liters per hectare* (1)	MJ per hectare** (2)	KWh per hectare (3)	KWh per sq m (4)
Ethanol from				
Corn[1]	3,730	89,517	24,886	2.489
Corn[2]	3,003	72,063	20,033	2.003
Corn stover[1]	1,544	37,051	10,300	1.030
Miscanthus[1]	6,945	166,676	46,336	4.634
Switchgrass[1]	2,009	48,208	13,402	1.340
Sugar cane[2]	6,744	161,861	44,997	4.500
Biodiesel[3]				
Oil palm	4,752	156,810	43,593	4.359
Coconut	2,151	70,997	19,737	1.974
Rapeseed	954	31,485	8,753	0.875
Peanut	842	27,781	7,723	0.772
Sunflower	767	25,312	7,037	0.704
Soybean	524	17,286	4,806	0.481

*1 US gallon = 3.78541178 l and 1 acre = 0.404685642 ha so 1 gallon per acre = 9.354 l/ha.

**Ethanol contains 23.4 MJ/l and biodiesel contains 35.7 MJ/l. 1 gigajoule (GJ) = 278 kWh. Source: Bioenergy Feedstock Information Network (http://bioenergy.ornl.gov/papers/misc/energy_conv.html).

Sources: Khanna et al. (2008), http://www.choicesmagazine.org/magazine/article.php?article=40, Woodrow Wilson Brazil Inst. Special report – pdf Brazil_SR_e3.pdf http://gristmill.grist.org/story/2006/2/7/12145/81957

[1] Khanna, 2008, http://www.choicesmagazine.org/magazine/article.php?article=40

[2] Woodrow Wilson Brazil Inst. Special report – pdf Brazil_SR_e3.pdf

[3] http://gristmill.grist.org/story/2006/2/7/12145/81957

In the photovoltaic process, photons from the sun energize electrons in a special material that channels them into an electric current. The electricity can be used immediately, for heat or to power electric devices, or stored in batteries. A different solar technology with some promise, but not discussed further involves using parabolic reflectors to concentrate solar energy and convert it to heat to drive steam or gas turbines to generate electricity. Both of these types of solar technologies produce electricity rather than liquid fuel.

This chapter has three goals. First, I present information on the raw availability of solar energy and compare that to the effective energy available at the end of the biological and PV processes. Second, I look at available evidence on the progress of photovoltaic technological improvements in converting solar energy into useful energy. Finally, I discuss briefly the issue of the technologies needed to use electricity in transportation instead of liquid fuels, i.e., plug-in cars and batteries.

2.2 From Solar Energy Input to Useful Energy Output

The sun delivers massive amounts of energy to the earth's surface. According to Wilkins et al. (2004), "Using current solar technology, an area just 100 miles by 100 miles (10,000 square miles) in the southwestern United States could generate as much energy as the entire nation currently consumes." Figure 2.1 shows the number of kilowatt hours (kWh) [1] delivered per m^2 per year, adjusted for the extent of cloud

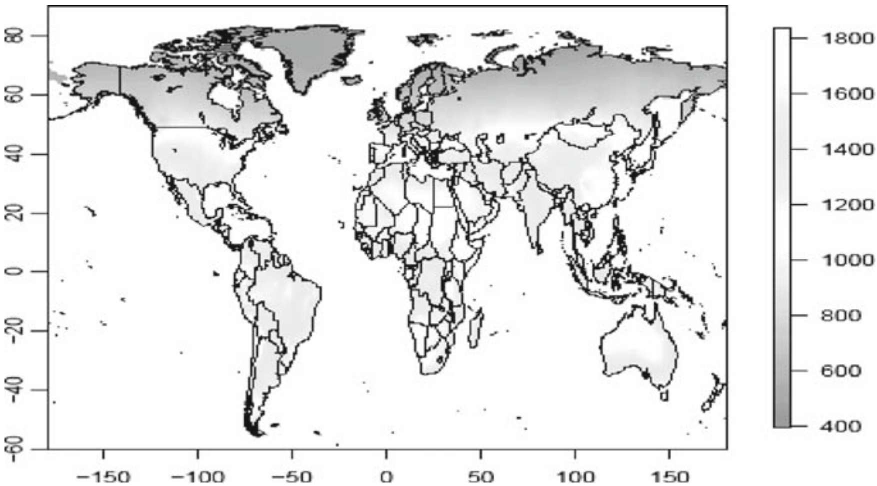

Fig. 2.1 Solor energy flux, kWh per m2 per year
Source: Personal communication from Robert Hijmans, International Rice Research Institute, based on a data set by Mark New and colleagues (New, Lister et al. 2002).

[1] The units used to report energy density of various sources vary. Biofuels energy densities are often reported in megajoules (MJ) or British thermal units (btu). Electricity is reported in kilowatt hours (kWh). One kWh is equivalent to 0.278 mj and 3,412 btus.

cover. The values range from 400 to 1,800 kWh per m^2 per year. Further from the equator, the energy delivers diminish somewhat because the tilt of the earth in its orbit around the sun reduces day length for part of the year. However, cloud cover plays a more important role in reducing effective solar energy. The highest values are found in desert regions, even those that are relatively far from the equator. Both plants and photovoltaics capture part of this raw energy and convert it into useful energy output.

2.3 Biofuel Energy Conversion

Table 2.1 reports several estimates of liquid fuel production and the resulting energy output from various biofuels crops. For ethanol, the largest reported volumes are from sugarcane and *Miscanthus*, although the *Miscanthus* value is based only on experimental results. Both crops can produce 6,500−7,000 l/ha under optimal conditions. Corn is a distant third at 3,700−4,000 l/ha. For biodiesel, oil palm performs best, producing almost 5,000 l/ha. These numbers are not typically reported by location but Fig. 2.2, which reproduces Fig. 2.1 in Khanna et al. 2008, provides some indirect evidence of the effects of the north-south gradient of solar energy availability. The cost per ton of dry matter from switchgrass is substantially lower in southern Illinois than northern Illinois principally because the dry matter yield is higher in the south.

The key column in Table 2.1 is column 4, which reports the effective energy availability per square meter of land used to grow the crop. *Miscanthus*, sugar cane, and oil palm have the highest effective energy outputs at 4.4−4.6 kWh per m^2 per year. Other crops produce much less energy. It is important to note that the values in column 4 do not take into account the energy used in processing the plant material into biofuels. Without attempting to provide quantitative estimates, it seems likely that palm oil requires the least energy input in processing, sugar cane somewhat more and *Miscanthus* the most because the cellulose must first be converted to a fermentable material.

Comparing the range of values of solar energy delivered to the earth's surface given in Fig. 2.1 (400 to 1,500 kWh per m^2 per year) with the effective energy delivered by the biofuels process (about 4.5 kWh per m^2 per year), it is clear that the combination of the crop conversion plus the processing conversion results in very little of the solar energy being made available for human use in liquid form. Loomis and Amthor (1996) (as cited in Reynolds et al. (2000)) report that the energy contained in a mature crop typically represents less than 5% of incident radiation received (radiation use efficiency, RUE). This inefficiency is caused by several factors. Chlorophyll has evolved to absorb wavelengths between 400 and 700 nm. It cannot take advantage of longer or shorter wavelengths, which photovoltaics can. In addition, some photosynthetically active radiation falls on nonphotosynthetically active cell components or structures such as dead leaves. Furthermore, plants can capture solar energy only during their growing season while photovoltaics work

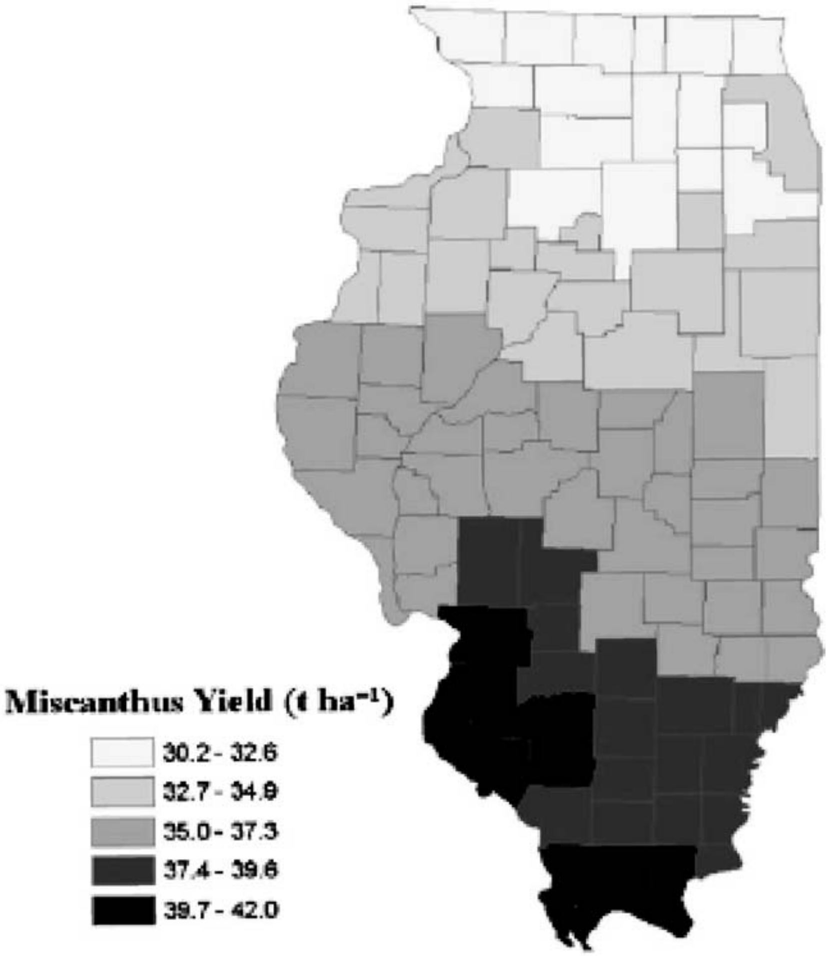

Fig. 2.2 Simulated Miscanthue yield
Source: Figure 3a in Khanna et al. (2008).

year round, and in fact are more efficient in colder temperatures. Finally, not all of the products of photosynthesis can be converted to biofuels.

Improvements in biofuels conversion can come from three sources – increasing productivity of existing fuel crops with improvements in RUE and biomass composition, switching to biofuels crops that extend their solar capture period by having a longer growing season, and improvements in the efficiency in converting the feedstocks to fuel. An example of the first source, increasing productivity of existing fuel crops, can be seen in productivity improvements in the Brazilian sugarcane industry (Fig. 2.3) where the ethanol yield per hectare increased over 3.5% per year between 1975 and 2003, at least some of which is because of increased sucrose production within the plant (although improved conversion efficiencies in the fermentation

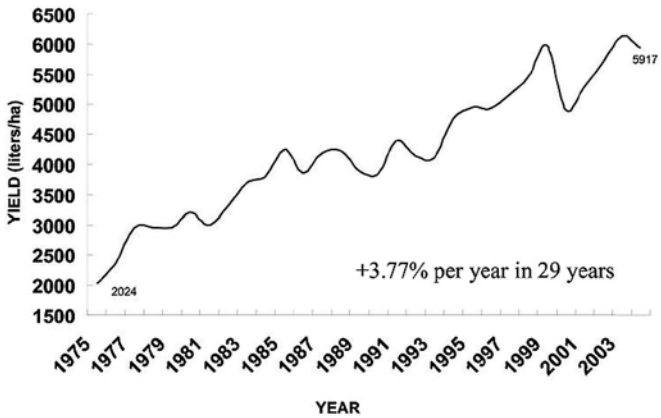

Fig. 2.3 Ethanol form sugarcane productivity increase in Brazil, 1975–2003
Source: Goldemberg (2008).

processes may have also contributed). For maize, Liska et al. (2009) report steady increases in maize grain productivity of over 0.1 mt/ha per year.

An example of the second source of productivity increase – switching to biofuels crops that extend their solar capture period by having a longer growing season – underlies the efforts to develop cellulosic ethanol, which allows any plant-based material to be a potential source of biofuels. In temperate climates, *Miscanthus* has two advantages over annual crops such as maize; as a perennial, it does not need to repeat the process of developing a root system every year, and it is cold tolerant allowing it to take advantage of more of the solar energy available throughout the year. Heaton et al. (2008) report harvestable dry matter yields of 10 to 30 mt/ha. An example of the third source of productivity increase – improvements in the efficiency in converting the feedstocks to fuel – is reported in Liska et al. (2009) who observe that "newer biorefineries have increased energy efficiency and reduced GHG emissions through the use of improved technologies, such as thermocompressors for condensing steam and increasing heat reuse; thermal oxidizers for combustion of volatile organic compounds (VOCs) and waste heat recovery; and raw-starch hydrolysis, which reduces heat requirements during fermentation" (p. 2).

2.4 Photovoltaic Energy Conversion

Photovoltaics convert solar energy directly into electricity. The amount of current depends on a wide range of factors including the design of the cell, the materials used to construct it, ambient temperature, and its orientation toward the sun. The photovoltaic phenomenon was first observed in the early 1800s and the first photovoltaic cell was constructed in the late 1800s.

The efficiency of a solar cell is defined as "the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit."[2] Figure 2.4 shows a history of solar cell efficiency improvements. Silicon wafer-based solar cell technologies, which make up most commercially available systems today, have efficiencies ranging from 6 to 20% commercially. High-efficiency thin-film technologies, currently available only in laboratories, achieve efficiencies of over 40%.

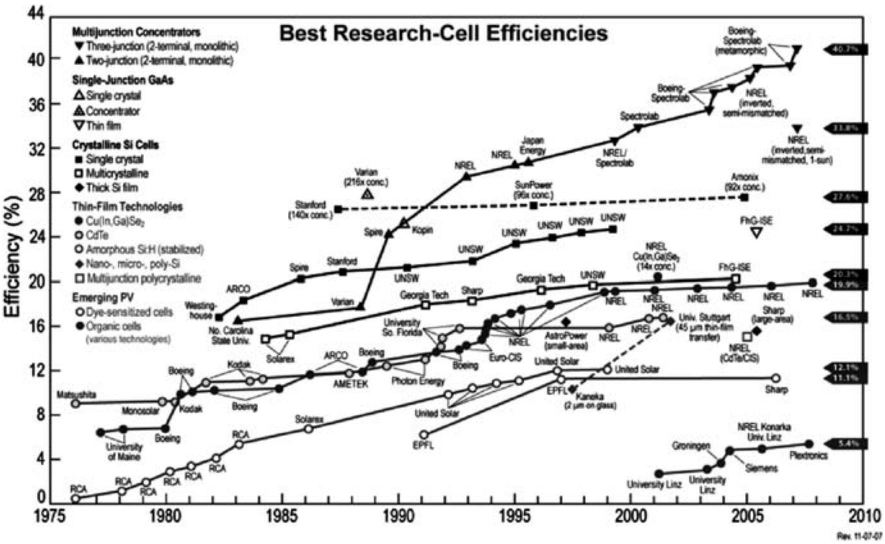

Fig. 2.4 Improvements in Research Sola Cell Efficiency
Source: Figure 1 in Kurtz (2008).

It is difficult to compare directly the efficiency of the biofuels process to photovoltaics in terms of converting solar (and other) energy into effective energy. The biofuels process includes processing energy not reported in Table 2.1. The photovoltaic efficiency values are essentially for systems installed to track the sun so that the optimal angle of incidence is always obtained. But even if we assume that today's commercial photovoltaic systems effectively deliver only one tenth of their official efficiency rating (say 0.6% instead of 6%), they would still produce 2.4 to 10.8 kWh per m^2 per year. A useful comparison is in the US Midwest where maize to ethanol technology is widespread and research on *Miscanthus* to ethanol is being undertaken. The average solar energy incidence is around 1,400 kWh per m^2 per year. With extremely conservative estimates of conversion efficiency, photovoltaics of the mid-2000s will generate about 8.4 kWh per m^2 per year. By contrast, current

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[2] "Photovoltaic efficiency is calculated using the ratio of the maximum power point, P_m, divided by the input light *irradiance* (E, in W/m^2) under standard test conditions (STC) and the *surface area* of the solar cell (A_c in m^2)." (Source: http://en.wikipedia.org/wiki/Solar_cell)

maize to ethanol technologies yield 2.0 to 2.5 kWh per m^2 per year and experimental results for *Miscanthus* are equivalent to 4.6 kWh per m^2 per year.

2.5 Photovoltaics and the Transportation Sector

Biofuels find their primary use in transportation, as partial or total substitutes for gasoline or diesel. Can photovoltaics play a similar role? The liquid fuel industry has tremendous advantages – widespread distribution networks (filling stations), an enormous pool of labor resources specialized in providing services through processing to distribution and repair, massive infrastructure for storage and transport, and a large installed base of vehicles. But addition of ethanol to this system in large volume presents technical difficulties. Transportation pipelines for oil cannot be readily changed to ethanol. Ethanol is hydrophilic, and the resulting water contamination can cause problems in storage facilities and engines not designed to use ethanol as fuel. Biodiesel presents problems in cold climates where it can congeal and block fuel lines.

There are numerous technical challenges to be met before solar-based electricity can compete commercially with liquid fuels in transportation (Graham 2001; MacLean and Lave 2003; Gaines et al. 2007; Karplus 2008; Bradley and Frank 2009). Commercially available vehicles that make partial use of electricity have been available only since the mid-1990s so both the engine and battery technologies needed to utilize solar-based electricity are still relatively new and evolving rapidly. Large-scale solar (arrays located in deserts) would require access to the grid, which is readily available in some places but not in all places. Distributed PVs (solar panels located on roof tops or back yards) are an option in locations where the grid is less well developed, but would need cost-effective battery technology to be useful for transportation.

The key technology, however, to make solar-based transportation technology possible, is improved batteries. Battery makers must develop battery technology that essentially emulates the energy-storage densities of liquid fuels. The batteries used in hybrid vehicles in the mid-2000s have insufficient capacity to provide the 300-mile range that would make it competitive with a gasoline-powered vehicle. However, substantial research is underway in battery technology, motivated in large part currently by the need for high-energy density storage for portable consumer electronics, in particular cell phones.

Axsen et al. (2008) provide an overview of the state of battery technology for use in transportation. The most popular hybrid vehicle, the Toyota Prius, initially used a lead acid battery technology but switched to an NiMH battery technology for its second-generation product. The consumer electronics industry has almost entirely shifted to lithium-ion (Li-ion) battery technology, which has much better performance characteristics. The much anticipated Chevrolet Volt hybrid (commercial release planned for 2010) is expected to use Li-ion batteries. According to Axsen et al. (p. iv), "Li-Ion battery technologies hold promise for achieving much higher power and energy density goals, due to lightweight material, potential for high voltage, and anticipated lower costs relative to NiMH. NiMH batteries could play an interim role in less demanding blended-mode designs, but it seems likely that falling Li-Ion battery prices may preclude even this role. However, Li-Ion batteries face drawbacks in longevity and safety which still need to be addressed for automotive applications."

2.6 Comparing the Costs of Energy from Biofuels and Photovoltaics

A meaningful comparison of the costs of delivering a unit of useful energy derived from sunlight via plants or photovoltaics is extremely complex. Creating ethanol from plants requires both significant fixed investments in capital equipment (processing facilities, tractors, transport equipment, etc.) and annual recurring costs (fuel for transport, applied nutrients, water, energy for processing). Manufacture of photovoltaics and their installation also have significant upfront costs but recurring expenditures are almost nonexistent. Said another way, the marginal cost of energy from photovoltaics is close to zero. Figure 2.5 taken from Wilkins et al. (2004) provides one estimate of the costs of photovoltaics (and solar water heating). These estimates, made in 2004, show photovoltaic-based electricity under 15 cents per kWh by 2010. This is still roughly 50% higher than the typical consumer rate of around 10 cents per kWh, but if plans to impose carbon emissions caps are implemented a 50% increase in the price of coal-based electricity would not be out of the question.

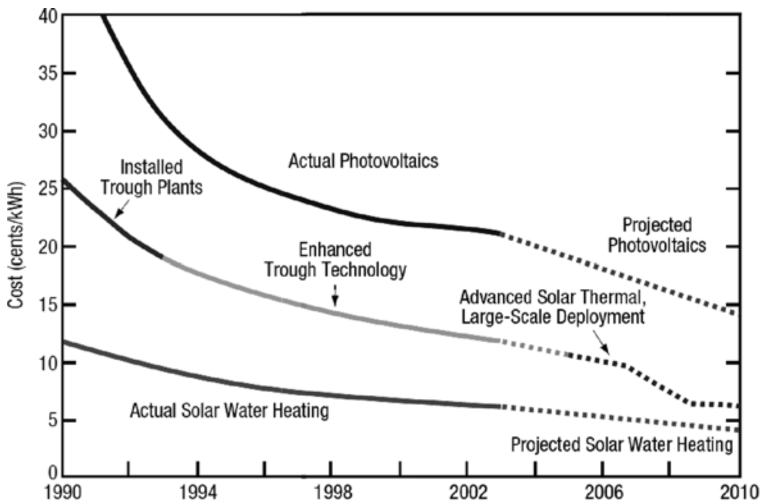

Fig. 2.5 Historical and Projected costs of various solar energy technologies
Source: Wilkins et al., (2004).

2.7 Concluding Remarks

This chapter has focused on one aspect of technical efficiency – the conversion of raw solar energy to a form that is useful to humans. Photovoltaics clearly dominate plants, with conversion rates with the commercial cells of the mid-2000s that are 2–10 times higher and operate throughout the year rather than just during the growing season. But photovoltaics provide electricity, which is not currently cost-effective for use in transportation. As research into photovoltaics and battery technology is still in its infancy, the potential for commercially viable technology breakthroughs seems high. The numerous negative externalities associated with biofuels (use of land that could otherwise be devoted to food, high water consumption, potentially noxious by-products) (Pimentel 2000; Gurgel et al. 2007; Rajagopal and Zilberman 2007; Hellegers et al. 2008; Searchinger et al. 2008), the still unproven commercial potential of cellulosic ethanol, and the inherent inefficiencies in capturing solar energy suggest we would be remiss not to continue substantial research efforts into cost-effective photovoltaics and automotive battery technology.

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