Energy Policy 46 (2012) 58–67

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The carbon footprint of indoor *Cannabis* production

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ARTICLE INFO

Article history:
Received 7 September 2011
Accepted 10 March 2012
Available online 17 April 2012

Keywords:
Energy
Buildings
Horticulture

ABSTRACT

The emergent industry of indoor *Cannabis* production – legal in some jurisdictions and illicit in others – utilizes highly energy intensive processes to control environmental conditions during cultivation. This article estimates the energy consumption for this practice in the United States at 1% of national electricity use, or $6 billion each year. One average kilogram of final product is associated with 4600 kg of carbon dioxide emissions to the atmosphere, or that of 3 million average U.S. cars when aggregated across all national production. The practice of indoor cultivation is driven by criminalization, pursuit of security, pest and disease management, and the desire for greater process control and yields. Energy analysts and policymakers have not previously addressed this use of energy. The unchecked growth of electricity demand in this sector confounds energy forecasts and obscures savings from energy efficiency programs and policies. While criminalization has contributed to the substantial energy intensity, legalization would not change the situation materially without ancillary efforts to manage energy use, provide consumer information via labeling, and other measures. Were product prices to fall as a result of legalization, indoor production using current practices could rapidly become non-viable.

1. Introduction

On occasion, previously unrecognized spheres of energy use come to light. Important historical examples include the pervasive air leakage from ductwork in homes, the bourgeoning energy intensity of computer datacenters, and the electricity "leaking" from billions of small power supplies and other equipment. Intensive periods of investigation, technology R&D, and policy development gradually ensue in the wake of these discoveries. The emergent industry of indoor *Cannabis* production appears to have joined this list.[1]

This article presents a model of the modern-day production process – based on public-domain sources – and provides first-order national scoping estimates of the energy use, costs, and greenhouse-gas emissions associated with this activity in the United States. The practice is common in other countries but a global assessment is beyond the scope of this report.

2. Scale of activity

The large-scale industrialized and highly energy-intensive indoor cultivation of *Cannabis* is a relatively new phenomenon, driven by criminalization, pursuit of security, pest and disease management, and the desire for greater process control and yields (U.S. Department of Justice, 2011a; World Drug Report, 2009). The practice occurs across the United States (Hudson, 2003; Gettman, 2006). The 415,000 indoor plants eradicated by authorities in 2009 (and 10.3 million including outdoor plantations) (U.S. Department of Justice, 2011a, b) presumably represent only a small fraction of total production.

Cannabis cultivation is today legal in 15 states plus the District of Columbia, although it is not federally sanctioned (Peplow, 2005). It is estimated that 24.8 million Americans are eligible to receive a doctor's recommendation to purchase or cultivate *Cannabis* under existing state laws, and approximately 730,000 currently do so (See Change Strategy, 2011). In California alone, 400,000 individuals are currently authorized to cultivate *Cannabis* for personal medical use, or sale for the same purpose to 2100 dispensaries (Harvey, 2009). Approximately 28.5 million people in the United States are repeat consumers, representing 11% of the population over the age of 12 (U.S. Office of National Drug Control Policy, 2011).

Cultivation is also substantial in Canada. An estimated 17,500 "grow" operations in British Columbia (typically located in residential buildings) are equivalent to 1% of all dwelling units Province-wide, with an annual market value of $7 billion (Easton, 2004).

Official estimates of total U.S. *Cannabis* production varied from 10,000 to 24,000 metric ton per year as of 2001, making it the nation's largest crop by value at that time (Hudson, 2003; Gettman, 2006). A recent study estimated national production at far higher levels (69,000 metric ton) (HIDTA, 2010). Even at the

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[1] This article substantively updates and extends the analysis described in Mills (2011).

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http://dx.doi.org/10.1016/j.enpol.2012.03.023

lower end of this range (chosen as the basis of this analysis), the level of activity is formidable and increasing with the demand for *Cannabis*.

No systematic efforts have previously been made to estimate the aggregate energy use of these activities.

3. Methods and uncertainties

This analysis is based on a model of typical *Cannabis* production, and the associated energy use for cultivation and transportation based on market data and first-principals buildings energy end-use modeling techniques. Data sources include equipment manufacturer data, trade media, the open literature, and interviews with horticultural equipment vendors. All assumptions used in the analysis are presented in Appendix A. The resulting normalized (per-kilogram) energy intensity is driven by the effects of indoor-environmental conditions, production processes, and equipment efficiencies.

Considerable energy use is also associated with transportation, both for workers and for large numbers of small-quantities transported and then redistributed over long distances before final sale.

This analysis reflects typical practices, and is thus intended as a "central estimate". While processes that use less energy on a per-unit-yield basis are possible, much more energy-intensive scenarios also occur. Certain strategies for lowering energy inputs (e.g., reduced illumination levels) can result in lower yields, and thus not necessarily reduce the ultimate energy-intensity per unit weight. Only those strategies that improve equipment and process energy efficiency, while not correspondingly attenuating yields would reduce energy intensity.

Due to the proprietary and often illicit nature of Cannabis cultivation, data are intrinsically uncertain. Key uncertainties are total production and the indoor fraction thereof, and the corresponding scaling up of relatively well-understood intensities of energy use per unit of production to state or national levels could result in 50% higher or lower aggregate results. Greenhouse-gas emissions estimates are in turn sensitive to the assumed mix of on- and off-grid power production technologies and fuels, as off-grid production (almost universally done with diesel generators) can – depending on the prevailing fuel mix in the grid – have substantially higher emissions per kilowatt-hour than grid power. Final energy costs are a direct function of the aforementioned factors, combined with electricity tariffs, which vary widely geographically and among customer classes. The assumptions about vehicle energy use are likely conservative, given the longer-range transportation associated with interstate distribution.

Some localities (very cold and very hot climates) will see much larger shares of production indoors, and have higher space-conditioning energy demands than the typical conditions assumed here. More in-depth analyses could explore the variations introduced by geography and climate, alternate technology configurations, and production techniques.

4. Energy implications

Accelerated electricity demand growth has been observed in areas reputed to have extensive indoor *Cannabis* cultivation. For example, following the legalization of cultivation for medical purposes (Phillips, 1998; Roth, 2005; Clapper et al., 2010) in California in 1996, Humboldt County experienced a 50% rise in per-capita residential electricity use compared to other parts of the state (Lehman and Johnstone, 2010).

Aside from sporadic news reports (Anderson, 2010; Quinones, 2010), policymakers and consumers possess little information on the energy implications of this practice. A few prior studies tangentially mentioning energy use associated with *Cannabis* production used cursory methods and under-estimate energy use significantly (Plecas et al., 2010 and Caulkins, 2010).

Driving the large energy requirements of indoor production facilities are lighting levels matching those found in hospital operating rooms (500-times greater than recommended for reading) and 30 hourly air changes (6-times the rate in high-tech laboratories, and 60-times the rate in a modern home). Resulting power densities are on the order of 2000 W/m^2, which is on a par with that of modern datacenters. Indoor carbon dioxide (CO_2) levels are often raised to 4-times natural levels in order to boost plant growth. However, by shortening the growth cycle, this practice may reduce final energy intensity.

Specific energy uses include high-intensity lighting, dehumidification to remove water vapor and avoid mold formation, space heating or cooling during non-illuminated periods and drying, pre-heating of irrigation water, generation of carbon dioxide by burning fossil fuel, and ventilation and air-conditioning to remove waste heat. Substantial energy inefficiencies arise from air cleaning, noise and odor suppression, and inefficient electric generators used to avoid conspicuous utility bills. So-called "grow houses" – residential buildings converted for *Cannabis* production – can contain 50,000 to 100,000 W of installed lighting power (Brady, 2004). Much larger facilities are also used.

Based on the model developed in this article, approximately 13,000 kW/h/year of electricity is required to operate a standard production module (a 1.2 × 1.2 × 2.4 m (4 × 4 × 8 ft) chamber). Each module yields approximately 0.5 kg (1 pound) of final product per cycle, with four or five production cycles conducted per year. A single grow house can contain 10 to 100 such modules.

To estimate national electricity use, these normalized values are applied to the lower end of the range of the aforementioned estimated production (10,000 t per year), with one-third of the activity takes place under indoor conditions. This indicates electricity use of about 20 TW/h/year nationally (including off-grid production). This is equivalent to that of 2 million average U.S. homes, corresponding to approximately 1% of national electricity consumption — or the output of 7 large electric power plants (Koomey et al., 2010). This energy, plus associated fuel uses (discussed below), is valued at $6 billion annually, with associated emissions of 15 million metric ton of CO_2 — equivalent to that of 3 million average American cars (Fig. 1 and Tables 1–3.)

Fuel is used for several purposes, in addition to electricity. The carbon dioxide injected into grow rooms to increase yields is produced industrially (Overcash et al., 2007) or by burning propane or natural gas within the grow room contributes about 1–2% to the carbon footprint and represents a yearly U.S. expenditure of $0.1 billion. Vehicle use associated with production and distribution contributes about 15% of total emissions, and represents a yearly expenditure of $1 billion. Off-grid diesel- and gasoline-fueled electric generators have per-kilowatt-hour emissions burdens that are 3- and 4-times those of average grid electricity in California. It requires 70 gallon of diesel fuel to produce one indoor *Cannabis* plant (or the equivalent yield per unit area), or 140 gallon with smaller, less-efficient gasoline generators.

In California, the top-producing state, indoor cultivation is responsible for about 3% of all electricity use, or 9% of household use.[2] This corresponds to the electricity use of 1 million average California homes, greenhouse-gas emissions equal to those from 1 million average cars, and energy expenditures of $3 billion per

[2] This is somewhat higher than estimates previously made for British Columbia, specifically, 2% of total Provincial electricity use or 6% of residential use (Garis, 2008; Bellett, 2010).

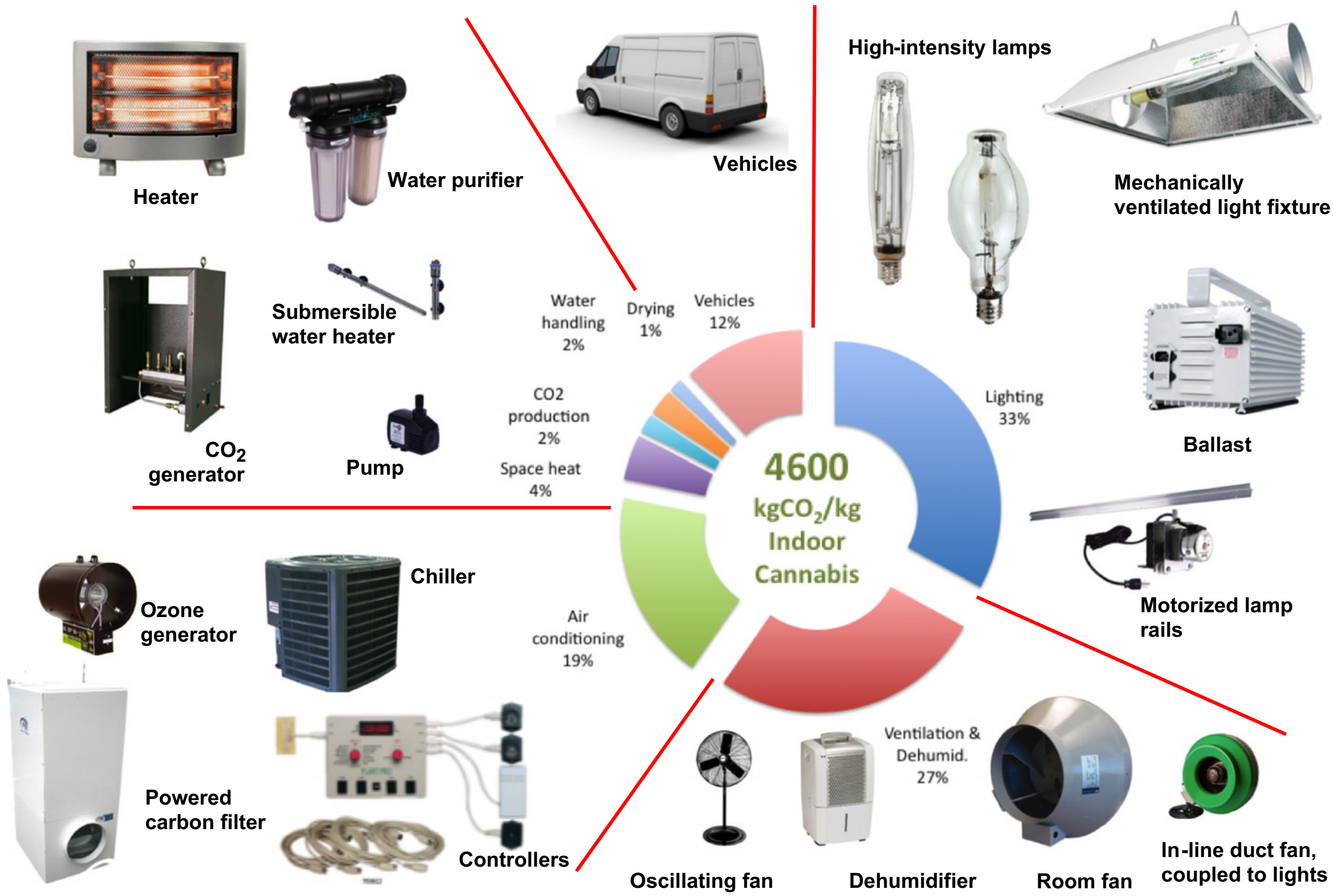

Fig. 1. Carbon footprint of indoor Cannabis production.

Table 1
Carbon footprint of indoor *Cannabis* production, by end use (average U.S conditions).

	Energy intensity (kW/h/kg yield)	Emissions factor (kgCO_2 emissions/kg yield)	
Lighting	2283	1520	33%
Ventilation & dehumid.	1848	1231	27%
Air conditioning	1284	855	19%
Space heat	304	202	4%
CO_2 injected to increase foliage	93	82	2%
Water handling	173	115	2%
Drying	90	60	1%
Vehicles		546	12%
Total	6074	4612	100%

Note: The calculations are based on U.S.-average carbon burdens of 0.666 kg/kW/h. "CO_2 injected to increase foliage" represents combustion fuel to make on-site CO_2. Assumes 15% of electricity is produced in off-grid generators.

year. Due to higher electricity prices and cleaner fuels used to make electricity, California incurs 50% of national energy costs but contributes only 25% of national CO_2 emissions from indoor *Cannabis* cultivation.

From the perspective of individual consumers, a single *Cannabis* cigarette represents 1.5 kg (3 pounds) of CO_2 emissions, an amount equal to driving a 44 mpg hybrid car 22 mile or running a 100-watt light bulb for 25 h, assuming average U.S. electricity emissions. The electricity requirement for one single production module equals that of an average U.S. home and twice that of an average California home. The added electricity use is equivalent to running about 30 refrigerators.

From the perspective of a producer, the national-average annual energy costs are approximately $5500 per module or $2500 per kilogram of finished product. This can represent half the wholesale value of the finished product (and a substantially lower portion at retail), depending on local conditions. For average U.S. conditions, producing one kilogram of processed *Cannabis* results in 4600 kg of CO_2 emissions to the atmosphere (and 50% more when off-grid diesel power generation is used), a very significant carbon footprint. The emissions associated with one kilogram of processed *Cannabis* are equivalent to those of driving across country 11 times in a 44-mpg car.

These results reflect typical production methods. Much more energy-intensive methods occur, e.g., rooms using 100% recirculated air with simultaneous heating and cooling, hydroponics, or energy end uses not counted here such as well-water pumps and water purification systems. Minimal information and consideration of energy use, coupled with adaptations for security and privacy (off-grid generation, no daylighting, odor and noise control) lead to particularly inefficient configurations and correspondingly elevated energy use and greenhouse-gas emissions.

The embodied energy of inputs such as soil, fertilizer, water, equipment, building materials, refinement, and retailing is not estimated here and should be considered in future assessments. The energy use for producing outdoor-grown *Cannabis* (approximately two-thirds of all production) is also not estimated here.

Table 2
Equivalencies.

Indoor Cannabis production consumes…	**3%**	of California's total electricity, and	**9%**	of California's household electricity	**1%**	of total U.S. electricity, and	2% of U.S. household electricity
U.S. Cannabis production & distribution energy costs…	**$ 6**	Billion, and results in the emissions of	**15**	Million tonnes per year of greenhouse gas emissions (CO_2)	Equal to the emissions of	**3**	million average cars
U.S. electricity use for Cannabis production is equivalent to that of…	**1.7**	Million average U.S. homes	**or**	**7**	Average U.S. power plants		
California Cannabis production and distribution energy costs...	**$ 3**	Billion, and results in the emissions of	**4**	Million tonnes per year of greenhouse gas emissions (CO_2)	Equal to the emissions of	**1**	Million average cars
California electricity use for Cannabis production is equivalent to that of…	**1**	Million average California homes					
A typical 4 × 4 × 8-ft production module, accomodating four plants at a time, consumes as much electricity as…	**1**	Average U.S. homes, or	**2**	Average California homes	or	**29**	Average new refrigerators
Every 1 kilogram of Cannabis produced using national-average grid power results in the emissions of…	**4.3**	Tonnes of CO_2	Equiva-lent to	**7**	Cross-country trips in a 5.3 l/100 km (44 mp g) car		
Every 1 kg of Cannabis produced using a prorated mix of grid and off-grid generators results in the emissions of…	**4.6**	Tonnes of CO_2	Equiva-lent to	**8**	Cross-country trips in a 5.3 l/100 km (44 mp g) car		
Every 1 kg of Cannabis produced using off-grid generators results in the emissions of…	**6.6**	Tonnes of CO_2	Equiva-lent to	**11**	Cross-country trips in a 5.3 l/100 km (44 mp g) car		
Transportation (wholesale + retail) consumes…	**226**	Liters of gasoline per kg	or	**$ 1**	Billion dollars annually, and	**546**	Kilograms of CO_2 per kilogram of final product
One Cannabis cigarette is like driving…	**37**	km in a 5.3 l/100 km (44 mpg) car	Emitting about	**2**	kg of CO_2, which is equivalent to operating a 100-watt light bulb for	**25**	Hours
Of the total wholesale price…	**49%**	Is for energy (at average U.S. prices)					

If improved practices applicable to commercial agricultural greenhouses are any indication, such large amounts of energy are not required for indoor *Cannabis* production.[3] The application of cost-effective, commercially-available efficiency improvements to the prototypical facility modeled in this article could reduce energy intensities by at least 75% compared to the typical-efficiency baseline. Such savings would be valued at approximately $40,000/year for a generic 10-module operation (at California energy prices and $10,000/year at U.S. average prices) (Fig. 2(a)–(b). These estimated energy use reductions reflect practices that are commonplace in other contexts such as more efficient components and controls (lights, fans, space-conditioning), use of daylight, optimized air-handling systems, and relocation of heat-producing equipment out of the cultivation room. Moreover, strain choice alone results in a factor-of-two difference in yields per unit of energy input (Arnold, 2011).

[3] See, e.g., this University of Michigan resource: http://www.hrt.msu.edu/energy/Default.htm

5. Energy intensities in context

Policymakers and other interested parties will rightfully seek to put these energy indicators in context with other activities in the economy.

One can readily identify other energy end-use activities with far greater impacts than that of *Cannabis* production. For example, automobiles are responsible for about 33% of U.S. greenhouse-gas emissions (USDOE, 2009), which is100-times as much as those produced by indoor *Cannabis* production (0.3%). The approximately 20 TW/h/year estimated for indoor *Cannabis* production is about one/third that of U.S. data centers (US EPA, 2007a, 2007b), or one-seventh that of U.S. household refrigerators (USDOE, 2008). These shares would be much higher in states where *Cannabis* cultivation is concentrated (e.g., one half that of refrigerators in California (Brown and Koomey, 2002)).

On the other hand, this level of energy use is high in comparision to that used for other indoor cultivation practices, primarily owing to the lack of daylighting. For comparison, the energy intensity of Belgian greenhouses is estimated at approximately 1000 MJ/m^2 (De Cock and Van Lierde, No date), or about 1% that estimated here for indoor *Cannabis* production.

Table 3
Energy indicators (average U.S. conditions).

	per cycle, per production module	per year, per production module	
Energy use			
Connected load		3,225	(watts/module)
Power density		2,169	(watts/m^2)
Elect	2756	12,898	(kW/h/module)
Fuel to make CO_2	0.3	1.6	(GJ)
Transportation fuel	27	127	(Gallons
On-grid results			
Energy cost	846	3,961	$/module
Energy cost		1,866	$/kg
Fraction of wholesale price		47%	
CO_2 emissions	1936	9,058	kg
CO_2 emissions		4,267	kg/kg
Off-grid results (diesel)			
Energy cost	1183	5,536	$/module
Energy cost		2,608	$/kg
Fraction of wholesale price		65%	
CO_2 emissions	2982	13,953	kg
CO_2 emissions		6,574	kgCO_2/kg
Blended on/off grid results			
Energy cost	897	4,197	$/module
Energy cost		1,977	$/kg
Fraction of wholesale price		49%	
CO_2 emissions	2093	9,792	kg
CO_2 emissions		4,613	kgCO_2/kg
Of which, indoor CO_2 production	9	42	kgCO_2
Of which, vehicle use			
Fuel use			
During production		79	Liters/kg
Distribution		147	Liters/kg
Cost			
During production		77	$/kg
Distribution		143	$/kg
Emissions			
During production		191	kgCO_2/kg
Distribution		355	kgCO_2/kg

Energy intensities can also be compared to those of other sectors and activities.

- Pharmaceuticals — Energy represents 1% of the value of U.S. pharmaceutical shipments (Galitsky et al., 2008) versus 50% of the value of Cannabis wholesale prices. The U.S. "Pharma" sector uses $1 billion/year of energy; Indoor Cannabis uses $6 billion.
- Other industries — Defining "efficiency" as how much energy is required to generate economic value, Cannabis comes out the highest of all 21 industries (measured at the three-digit SIC level). At ~20 MJ per thousand dollars of shipment value (wholesale price), Cannabis is followed next by paper (~14), nonmetallic mineral products (~10), primary metals (~8), petroleum and coal products (~6), and then chemicals (~5) (Fig. 3). However, energy intensities are on a par with *Cannabis* in various subsectors (e.g., grain milling, wood products, rubber) and exceed those of *Cannabis* in others (e.g., pulp mills).
- Alcohol — The energy used to produce one marijuana cigarette would also produce 18 pints of beer (Galitsky et al., 2003).
- Other building types — Cannabis production requires 8-times as much energy per square foot as a typical U.S. commercial building (4x that of a hospital and 20x that of a building for religious worship), and 18-times that of an average U.S. home (Fig. 4).

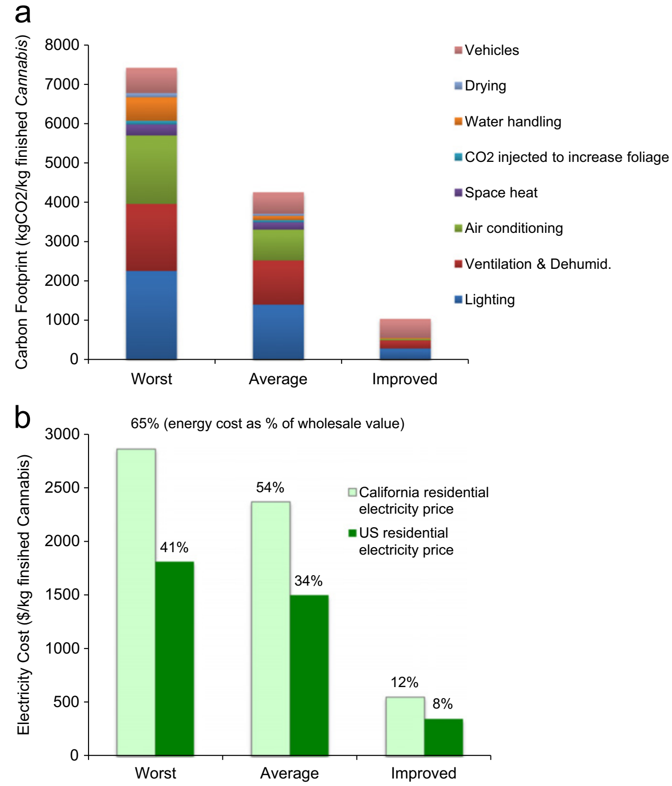

Fig. 2. Carbon footprint and energy cost for three levels of efficiency. (a) Indoor cannabis: carbon footprint. (b) Indoor cannabis: electricity cost. Assumes a wholesale price of $4400/kg. Wholesale prices are highly variable and poorly documented.

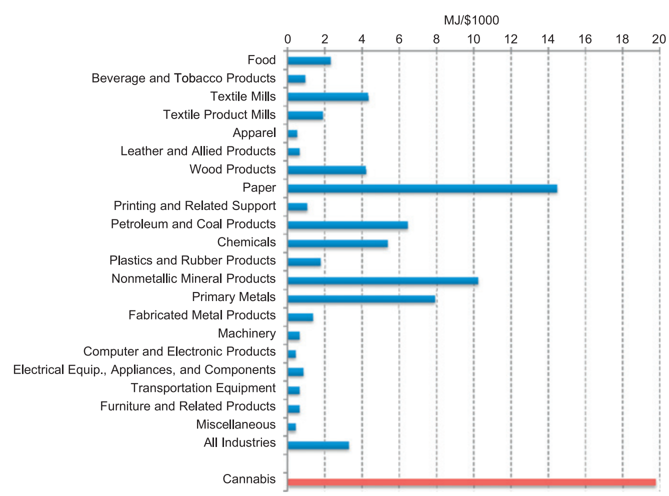

Fig. 3. Comparative energy intensities, by sector (2006).

6. Outdoor cultivation

Shifting cultivation outdoors can nearly eliminate energy use for the cultivation process. Many such operations, however, require water pumping as well as energy-assisted drying techniques. Moreover, vehicle transport during production and distribution remains part of the process, more so than for indoor operations.

A common perception is that the potency of *Cannabis* produced indoors exceeds that of that produced outdoors, leading

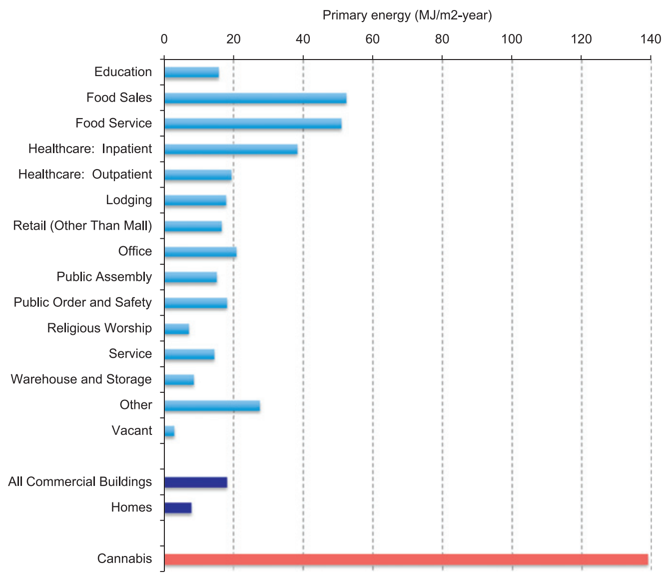

Fig. 4. Comparative energy intensities, by U.S. building type (2003).

Table A1
Configuration, environmental conditions, set-points.

Production parameters		
Growing module	1.5	m^2 (excl. walking area)
Number of modules in a room	10	
Area of room	22	m^2
Cycle duration	78	days
Production continuous throughout the year	4.7	cycles
Illumination	Leaf phase	Flowering phase
Illuminance	25 klux	100 klux
Lamp type	Metal halide	High-pressure sodium
Watts/lamp	600	1000
Ballast losses (mix of magnetic & digital)	13%	0.13
Lamps per growing module	1	1
Hours/day	18	12
Days/cycle	18	60
Daylighting	None	none
Ventilation		
Ducted luminaires with "sealed" lighting compartment	150	CFM/1000 W of light (free flow)
Room ventilation (supply and exhaust fans)	30	ACH
Filtration	Charcoal filters on exhaust; HEPA on supply	
Oscilating fans: per module, while lights on	1	
Water		
Application	151	liters/room-day
Heating	Electric submersible heaters	
Space conditioning		
Indoor setpoint — day	28	C
Indoor setpoint — night	20	C
AC efficiency	10	SEER
Dehumidification	7x24	hours
CO_2 production — target concentration (mostly natural gas combustion in space)	1500	ppm
Electric space heating	When lights off to maintain indoor setpoint	
Target indoor humidity conditions	40–50%	
Fraction of lighting system heat production removed by luminaire ventilation	30%	
Ballast location	Inside conditioned space	
Drying		
Space conditioning, oscillating fans, maintaining 50% RH, 70–80F	7	Days
Electricity supply		
grid	85%	
grid-independent generation (mix of diesel, propane, and gasoline)	15%	

consumers to demand *Cannabis* produced indoors. Federal sources (National Drug Intelligence Center, 2005) as well as independent testing laboratories (Kovner, 2011) actually find similar potencies when best practices are used.

Illegal clearing of land is common for multi-acre plantations, and, depending on the vegetation type, can accordingly mobilize greenhouse-gas emissions. Standing forests (a worst-case scenario) hold from 125 to 1500 t of CO_2 per hectare, depending on tree species, age, and location (National Council for Air and Soil Improvement, 2010). For biomass carbon inventories of 750 t/ha and typical yields (5000 kg/ha) (UNODC, 2009), associated biomass-related CO_2 emissions would be on the order of 150 kg CO_2/kg *Cannabis* (for only one harvest per location), or 3% of that associated with indoor production. These sites typically host on the order of 10,000 plants, although the number can go much higher (Mallery, 2011). When mismanaged, the practice of outdoor cultivation imposes multiple environmental impacts aside from energy use. These include deforestation; destruction of wetlands, runoff of soil, pesticides, insecticides, rodenticides, and human waste; abandoned solid waste; and unpermitted impounding and withdrawals of surface water (Mallery, 2011; Revelle, 2009). These practices can compromise water quality, fisheries, and other ecosystem services.

7. Policy considerations

Current indoor *Cannabis* production and distribution practices result in prodigious energy use, costs, and unchecked greenhouse-gas pollution. While various uncertainties exist in the analysis, the overarching qualitative conclusions are robust. More in-depth analysis and greater transparency of the energy impacts of this practice could improve decision-making by policymakers and consumers alike.

There is little, if any, indication that public policymakers have incorporated energy and environmental considerations into their deliberations on *Cannabis* production and use. There are additional adverse impacts of the practice that merit attention, including elevated moisture levels associated with indoor cultivation that can cause extensive damage to buildings,[4] as well as electrical fires caused by wiring out of compliance with safety codes (Garis, 2008). Power theft is common, transferring those energy costs to the general public (Plecas et al., 2010). As noted above, simply shifting production outdoors can invoke new environmental impacts if not done properly.

Energy analysts have also not previously addressed the issue. Aside from the attention that any energy use of this magnitude normally receives, the hidden growth of electricity demand in this sector confounds energy forecasts and obscures savings from energy efficiency programs and policies. For example, Auffhammer and Aroonruengsawat (2010) identified a

[4] For observations from the building inspectors community, see http://www.nachi.org/marijuana-grow-operations.htm

Table A2
Assumptions and conversion factors.

Service levels		
Illuminance*	25–100	1000 lux
Airchange rates*	30	Changes per hour
Operations		
Cycle duration**	78	Days
Cycles/year**	4.7	Continuous production
Airflow**	96	Cubic feet per minute, per module
Lighting		
Leafing phase		
Lighting on-time*	18	hrs/day
Duration*	18	days/cycle
Flowering phase		
Lighting on-time*	12	hrs/day
Duration*	60	days/cycle
Drying		
Hours/day*	24	hrs
Duration*	7	days/cycle
Equipment		
Average air-conditioning age	5	Years
Air conditioner efficiency [Standards increased to SEER 13 on 1/23/2006]	10	SEER
Fraction of lighting system heat production removed by luminaire ventilation	0.3	
Diesel generator efficiency*	27%	55 kW
Propane generator efficiency*	25%	27 kW
Gasoline generator efficiency*	15%	5.5 kW
Fraction of total prod'n with generators*	15%	
Transportation: Production phase (10 modules)	25	Miles roundtrip
Daily service (1 vehicle)	78	Trips/cycle. Assume 20% live on site
Biweekly service (2 vehicles)	11.1	Trips/cycle
Harvest (2 vehicles)	10	Trips/cycle
Total vehicle miles**	2089	Vehicle miles/cycle
Transportation: Distribution		
Amount transported wholesale	5	kg per trip
Mileage (roundtrip)	1208	km/cycle
Retail (0.25oz $\times$ 5 miles roundtrip)	5668	Vehicle-km/cycle
Total**	6876	Vehicle-km/cycle
Fuel economy, typical car [a]	10.7	l/100 km
Annual emissions, typical car [a]	5195	kgCO$_2$
	0	kgCO$_2$/mile
Annual emissions, 44-mpg car**	2,598	kgCO$_2$
	0.208	kgCO$_2$/mile
Cross-country U.S. mileage	4493	km
Fuels		
Propane [b]	25	MJ/liter
Diesel [b]	38	MJ/liter
Gasoline [b]	34	MJ/liter
Electric generation mix*		
Grid	85%	share
Diesel generators	8%	share
Propane generators	5%	share
Gasoline generators	2%	share
Emissions factors		
Grid electricity — U.S. [c]	0.609	kgCO$_2$/kW/h
Grid electricity — CA [c]	0.384	kgCO$_2$/kW/h
Grid electricity — non-CA U.S. [c]	0.648	kgCO$_2$/kW/h
Diesel generator**	0.922	kgCO$_2$/kW/h
Propane generator**	0.877	kgCO$_2$/kW/h
Gasoline generator**	1.533	kgCO$_2$/kW/h
Blended generator mix**	0.989	kgCO$_2$/kW/h
Blended on/off-grid generation — CA**	0.475	kgCO$_2$/kW/h
Blended on/off-grid generation — U.S.**	0.666	kgCO$_2$/kW/h
Propane combustion	63.1	kgCO$_2$/MBTU
Prices		
Electricity price — grid (California — PG&E) [d]	0.390	per kW/h (Tier 5)
Electricity price — grid (U.S.) [e]	0.247	per kW/h
Electricity price — off-grid**	0.390	per kW/h
Electricity price — blended on/off — CA**	0.390	per kW/h
Electricity price — blended on/off — U.S.**	0.268	per kW/h
Propane price [f]	0.58	$/liter
Gasoline price — U.S. average [f]	0.97	$/liter
Diesel price — U.S. average [f]	1.05	$/liter
Wholesale price of Cannabis [g]	4,000	$/kg
Production		
Plants per production module*	4	
Net production per production module [h]	0.5	kg/cycle
U.S. production (2011) [i]	10,000	metric tonnes/y
California production (2011) [i]	3,902	metric tonnes/y
Fraction produced indoors [i]	33%	
U.S. indoor production modules**	1,570,399	
Calif indoor production modules**	612,741	
Cigarettes per kg**	3,000	
Other		
Average new U.S. refrigerator	450	kW/h/year
	173	kgCO$_2$/year (U.S. average)
Electricity use of a typical U.S. home — 2009 [j]	11,646	kW/h/year
Electricity use of a typical California home — 2009 [k]	6,961	kW/h/year

Notes:
* Trade and product literature; interviews with equipment vendors.
** Calculated from other values.
Notes for Table A2.
[a]. U.S. Environmental Protection Agency., 2011.
[b]. *Energy conversion factors*, U.S. Department of Energy, http://www.eia.doe.gov/energyexplained/index.cfm?page=about_energy_units, [Accessed February 5, 2011].
[c]. United States: (USDOE 2011); California (Marnay et al., 2002).
[d]. Average prices paid in California and other states with inverted-block tariffs are very high because virtually all consumption is in the most expensive tiers. Here the PG&E residential tariff as of 1/1/11, Tier 5 is used as a proxy for California http://www.pge.com/tariffs/ResElecCurrent.xls, (Accessed February 5, 2011). In practice a wide mix of tariffs apply, and in some states no tier structure is in place, or the proportionality of price to volume is nominal.
[e]. State-level residential prices, weighted by *Cannabis* production (from Gettman. 2006) with actual tariffs and U.S. Energy Information Administration, "Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State", http://www.eia.doe.gov/electricity/epm/table5_6_a.html, (Accessed February 7, 2011)
[f]. U.S. Energy Information Administration, Gasoline and Diesel Fuel Update (as of 2/14/2011) – see http://www.eia.gov/oog/info/gdu/gasdiesel.asp Propane prices – http://www.eia.gov/dnav/pet/pet_pri_prop_a_EPLLPA_PTA_dpgal_m.htm, (Accessed April 3, 2011).
[g]. Montgomery, 2010.
[h]. Toonen et al., 2006); Plecas et al., 2010.
[i]. *Total Production*: The lower value of 10,000 t per year is conservatively retained. Were this base adjusted to 2011 values using 10.9%/year net increase in number of consumers between 2007 and 2009 per U.S. Department of Health and Human Services (2010), the result would be approximately 17 million tonnes of total production annually (indoor and outdoor). *Indoor Share of Total Production*: The three-fold changes in potency over the past two decades, reported by federal sources, are attributed at least in part to the shift towards indoor cultivation See http://www.justice.gov/ndic/pubs37/37035/national.htm and (Hudson, 2003). A weighted-average potency of 10% THC (U.S. Office of Drug Control Policy, 2010) reconciled with assumed 7.5% potency for outdoor production and 15% for indoor production implies 33.3%::67.7% indoor::outdoor production shares. For reference, as of 2008, 6% of eradicated plants were from indoor operations, which are more difficult to detect than outdoor operations. A 33% indoor share, combined with per-plant yields from Table 2, would correspond to a 4% eradication success rate for the levels reported (415,000 indoor plants eradicated in 2009) by the U.S. Drug Enforcement Agency (http://www.justice.gov/dea/programs/marijuana.htm). Assuming 400,000 members of medical Cannabis dispensaries in California (each of which is permitted to cultivate), and 50% of these producing in the generic 10-module room assumed in this analysis, output would slightly exceed this study's estimate of total statewide production. In practice, the vast majority of indoor production is no doubt conducted outside of the medical marijuana system.
[j]. Total U.S. electricity sales: U.S. energy information administration, "retail sales of electricity to ultimate customers: Total by end-use sector" http://www.eia.gov/cneaf/electricity/epm/table5_1.html, (Accessed March 5, 2011)
[k]. California Energy Commission, 2009; 2011.

statistically significant, but unexplained, increase in the growth rate for residential electricity in California during the years when indoor *Cannabis* production grew as an industry (since the mid-1990s).

Table A3
Energy model.

ELECTRICITY	Energy type	Penetration	Rating (Watts or %)	Number of 4 × 4 × 8-ft production modules served	Input energy per module	Units	Hours/day (leaf phase)	Hours/day (flower phase)	Days/cycle (leaf phase)	Days/cycle (flower phase)	kW/h/cycle	kW/h/year per production module
Light												
Lamps (HPS)	elect	100%	1,000	1	1,000	W		12		60	720	3,369
Ballasts (losses)	elect	100%	13%	1	130	W		12		60	94	438
Lamps (MH)	elect	100%	600	1	600	W	18		18		194	910
Ballast (losses)	elect	100%	0	1	78	W	18		18		25	118
Motorized rail motion	elect	5%	6	1	0.3	W	18	12	18	60	0	1
Controllers	elect	50%	10	10	1	W	24	24	18	60	2	9
Ventilation and moisture control												
Luminare fans (sealed from conditioned space)	elect	100%	454	10	45	W	18	12	18	60	47	222
Main room fans — supply	elect	100%	242	8	30	W	18	12	18	60	31	145
Main room fans — exhaust	elect	100%	242	8	30	W	18	12	18	60	31	145
Circulating fans (18")	elect	100%	130	1	130	W	24	24	18	60	242	1,134
Dehumidification	elect	100%	1,035	4	259	W	24	24	18	60	484	2,267
Controllers	elect	50%	10	10	1	W	24	24	18	60	2	9
Spaceheat or cooling												
Resistance heat or AC [when lights off]		90%	1,850	10	167	W	6	12	18	60	138	645
Carbon dioxide Injected to Increase foliage												
Parasitic electricity	elect	50%	100	10	5	W	18	12	18	60	5	24
AC (see below)	elect	100%										
In-line heater	elect	5%	115	10	0.6	W	18	12	18	60	1	3
Dehumidification (10% adder)	elect	100%	104	0	26	W	18	12	18	60	27	126
Monitor/control	elect	100%	50	10	5	W	24	24	18	60	9	44
Other												
Irrigation water temperature control	elect	50%	300	10	15	W	18	12	18	60	19	89
Recirculating carbon filter [sealed room]	elect	20%	1,438	10	29	W	24	24	18	60	54	252
UV sterilization	Elect	90%	23	10	2.1	W	24	24	18	60	4	18
Irrigation pumping	elect	100%	100	10	10	W	2	2	18	60	2	7
Fumigation	elect	25%	20	10	1	W	24	24	18	60	1	4
Drying												
Dehumidification	elect	75%	1,035	10	78	W		24		7	13	61
Circulating fans	elect	100%	130	5	26	W		24		7	4	20
Heating	elect	75%	1,850	10	139	W		24		7	23	109
Electricity subtotal	elect										2,174	10,171
Air-conditioning				10	420	W					583	2,726
Lighting loads				10		W					259	1,212
Loads that can be remoted	elect	100%	1,277	10		W					239	1,119
Loads that can't be remoted	elect	100%	452	10		W					85	396
CO2-production heat removal	elect	45%	1,118	17		W	18	12	18	60	—	—
Electricity Total	elect				3,225	W					2,756	12,898

FUEL	Units	Technology Mix	Rating (BTU/h)	Number of 4 × 4 × 8-ft production modules served	Input energy per module		Hours/day (leaf phase)	Hours/day (flower phase)	Days/cycle (leaf phase)	Days/cycle (flower phase)	GJ or $kgCO_2$/cycle	GJ or $kgCO_2$/year
On-site CO_2 production												
Energy use	propane	45%	11,176	17	707	kJ/h	18	12	18	60	0.3	1.5
CO2 production – > emissions	kg/CO_2										20	93
Externally produced Industrial CO_2		5%		1	0.003	liters CO_2/hr	18	12	18	60	0.6	2.7
Weighted-average on-site/purchased	$kgCO_2$										2	10

For *Cannabis* producers, energy-related production costs have historically been acceptable given low energy prices and high product value. As energy prices have risen and wholesale commodity prices fallen, high energy costs (now 50% on average of wholesale value) are becoming untenable. Were product prices to fall as a result of legalization, indoor production could rapidly become unviable.

For legally sanctioned operations, the application of energy performance standards, efficiency incentives and education, coupled with the enforcement of appropriate construction codes could lay a foundation for public-private partnerships to reduce undesirable impacts of indoor *Cannabis* cultivation.[5] There are early indications of efforts to address this.[6] Were such operations to receive some form of independent certification and product labeling, environmental impacts could be made visible to otherwise unaware consumers.

Acknowledgment

Two anonymous reviewers provided useful comments that improved the paper. Scott Zeramby offered particularly valuable insights into technology characteristics, equipment configurations, and market factors that influence energy utilization in this context and reviewed earlier drafts of the report.

Appendix A

See Tables A1–A3.

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