

Energy for water and water for energy on Maui Island, Hawaii

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LETTER

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Abstract

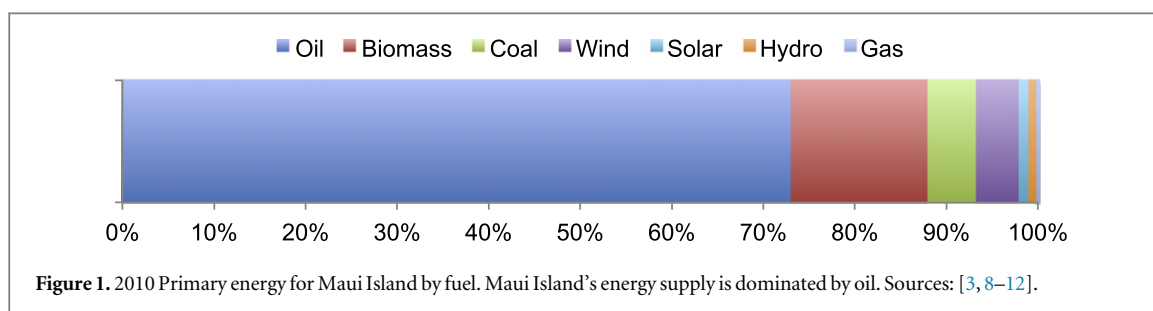
Energy and water systems are interconnected. This work first characterizes 2010 primary energy demand for direct water services and local freshwater demand for energy on Maui Island, Hawaii, then investigates scenarios for future changes in these demands. The goal of this manuscript is to dissect the relationship and trends of energy–water connections to inform policymaking decisions related to water and energy planning. Analysis proceeds by inventorying water and energy flows and adjusting to a 2010 base year, then applying intensity factors for energy or water used at a given stage for a given sector to determine absolute energy and water demands for the isolated system of Maui Island. These bottom-up, intensity-based values are validated against published data where available. Maui consumes about 0.05% of its freshwater for energy (versus >6% for the US on average) and about 32% of its electricity (19% of its on-island primary energy) for direct water services (versus 8% of primary energy for the US on average). These values could change with policy choices like increased instream flows, higher wastewater treatment standards, electricity fuel mix changes, desalination, or increased biofuels production. This letter contributes a granular assessment of both energy for water and water for energy in a single isolated system, highlighting opportunities to address energy–water interdependencies in a context that could be relevant in other communities facing similar choices.

Introduction

Water and energy systems are interdependent and closely related, with the availability of one resource often subject to availability of the other. Water and wastewater plants require energy for pumping and treating water, and water distribution systems and end users use energy to move and condition water; power plants use water for cooling, and fuel extraction often uses or produces water. In many areas, energy is limited by water because of power plant cooling needs [1]. On Maui Island in Hawaii, the most populated of Maui County's three inhabited islands, the reverse relationship is more relevant: Maui's freshwater supply is limited by energy availability, while its energy supply remains fairly independent of local freshwater.

Maui is a useful testbed for analysis due both to a level of climatological and water demand profile

diversity more commonly seen at continental scales and to very high energy prices that enable analysis of actions given the types of prices that might follow from policy actions such as putting a price on carbon dioxide emissions. About half the area of Rhode Island, Maui hosts both deserts and one of the wettest places on earth [2]. Despite its substantial wind, solar, and other energy resources, Maui relies on imported petroleum for over 70% of its on-island primary energy use [3] (figure 1). While Maui's energy supplies are not currently dependent on local freshwater availability, largely because of Maui's reliance on imported fuels and its mainly brackish water- or air-cooled electricity system, Maui's use of its substantial water resources is heavily limited by access to energy. This energy limitation is largely due to spatial mismatches between the location of population centers and aquifers, pumping intensity for water at high elevations, and high



electricity prices that render additional water pumping cost-prohibitive [4–7].

Maui's energy–water nexus is particularly interesting given two of the island's major goals: expanding freshwater supplies and expanding use of local, renewable energy. Both goals are considered urgent by policymakers, as Maui faces a likely drier future [8, 13, 14], seeks to ensure stewardship of resources held in public trust by returning surface water to its natural setting with stricter instream flow standards [15], and, as part of Hawaii, targets 40% local, renewable energy use by 2030 [16]. These goals might appear to be at odds with each other, as expanding water supplies could require more energy use—for example, for pumping water from distant aquifers, treating wastewater to higher standards for reuse, or for desalination—and increasing use of local energy resources in the form of irrigated biofuels, a commonly discussed option, could require a reallocation of significant volumes of water from agriculture to energy production. However, there are also important potential synergies, especially considering that energy resources like wind and solar photovoltaic power are abundant on Maui, essentially water independent, and potentially available for cost effective use in the water system.

While meeting Maui's water and energy goals need not be mutually exclusive, understanding the current status of the island's energy–water nexus is a first step to identifying the most relevant interactions. Accordingly, this work seeks to answer the following research questions: how much water does Maui use for its energy system, how much energy does Maui use for its water system, and how might demand change in response to likely future developments like increased demand for potable water or increased production of local biofuels? Characterizing water for energy and energy for water is done jointly to fully capture the nature of the energy–water nexus for Maui Island. Maui is selected as a research location due to its relative isolation, scale, range of water conditions, and relevance for other regions. For example, Maui is one of many communities currently implementing or considering environmental and energy policies that can affect linked water-energy systems, like instream flow standards, liquefied natural gas (LNG) imports, and renewable portfolio standards (RPS).

Background

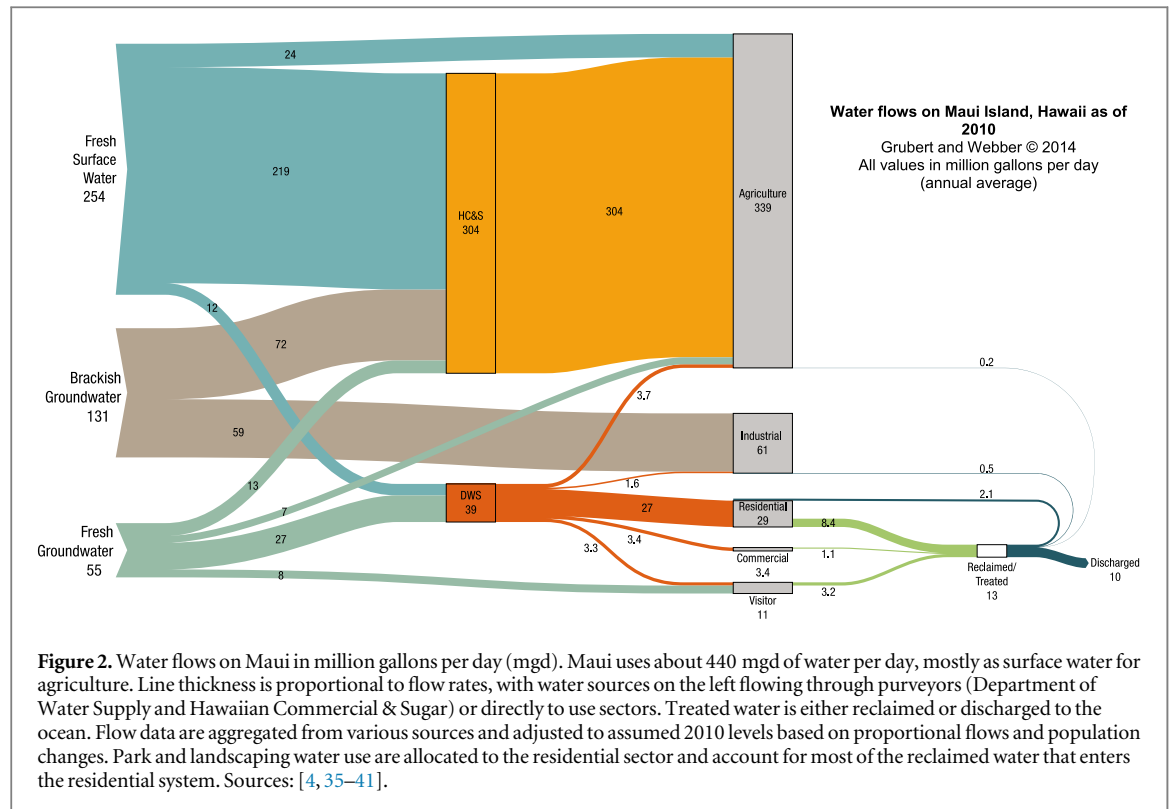
This letter presents analysis of Maui's energy–water nexus, addressing both energy use for water systems and water use for energy systems, focusing on local primary energy and local freshwater on Maui Island, Hawaii. The following sections describe the context of the work and its contributions, including its simultaneous and internally consistent analysis of both energy for water and water for energy in a given system.

Energy for water

Maui Island is not unique in its significant use of energy for water systems: an estimate for the entire United States based on 2010 data suggests that 8% of US primary energy is used for direct water services, namely to convey (pressurize and pump), treat, and condition (heat and cool) water for use in non-steam applications [17]. In places with significant conveyance needs and elevation gradients, like California, the number is even higher: based on Energy Commission Reports, EIA data, and California power plant heat rates, California spent about 15% of its primary energy on direct water services in 2001 [18–22].

Determining the amount of energy used for water services is straightforward given the right information, namely precise water flows and energy intensities associated with a service, but these data are not always readily available. Energy intensities associated with particular processes like water pumping and water treatment have been published in the scholarly literature [1, 6, 23–25]. However, ultimately, the total amount of energy used for water services can be a more important metric for decision-makers who need to know the potential for meaningful savings or synergies, for example in the context of urban metabolism-based planning [26]. This letter contributes to the literature with a granular analysis of absolute energy use for water services in an isolated system, following work on energy for water for a given location or process like [17, 21, 22, 27–30]. Further, this letter uses top-down published values for energy use at particular points in the water system to validate the use of intensity values for a real system. The remainder of this section introduces Maui as a testbed.

Maui's particular characteristics mean that it is unusually dependent on energy to access its significant freshwater resources. While Maui has an estimated



760 million gallons per day (mgd) of available fresh-water resources, both as surface (330 mgd, [29]) and groundwater (430 mgd, [31]), it is highly dependent on pumping groundwater both long horizontal distances from wet areas to more populated drier areas and long vertical distances from the freshwater lenses resting above seawater in Maui's volcanic rock up to users at high elevations on the flanks of its two volcanoes. A result of this dependence on pumping is that Maui's water delivery systems are relatively energy-intensive, which means that Maui potentially faces economic water scarcity due to energy limitations despite its large water resources. Since most of Maui's fresh surface water is allocated to environmental and agricultural uses, further freshwater supplies must come either from displacing agriculture or by spending more energy to pump, treat, and reclaim water.

Overall, Maui Island consumes about 440 mgd of water, including about 140 mgd of non-potable, brackish groundwater for applications like irrigation and industrial cooling (figure 2; note that some of this 'consumption', particularly agriculture and industrial consumption, is returned to shallow aquifers that also serve as water sources). Maui residents use relatively more freshwater per person than other Americans, with total per capita freshwater use of about 2100 gal/person-day (excluding embodied water in imports) versus about 1800 gal/person-day for the United States overall [32] and residential use of about 200 gal/person-day versus about 70 gal/person-day for a set of 10 OECD countries [33] and 170 gal/person-day for the United States overall [34]. This relatively high

intensity indicates potential opportunities for conservation as an alternative to increased supply.

Three organizations are particularly relevant to energy use for direct water services on Maui Island: the Department of Water Supply (DWS), the Wastewater Reclamation Division, and Hawaiian Commercial & Sugar Company (HC&S), Maui's last remaining agricultural plantation. As of 2010, DWS supplies 38 mgd for domestic and agricultural water as both surface and groundwater [11], accounting for over 80% of the domestic water supply on Maui Island [4]. About 70% of the DWS supply is groundwater from wells that, weighted by capacity, average almost 700 feet deep—and many are significantly deeper [42]. In addition to DWS supply, private domestic wells provide about 7 mgd of potable groundwater [4].

Unlike groundwater, which does not need treatment before use [29], surface water must be treated before use to be considered potable, and DWS runs several water treatment plants to treat surface water to potable standards [43]. Ten percent of combined Maui Island DWS-supplied drinking water, including some that has been treated, supplies agricultural users [11].

The Maui County Wastewater Reclamation Division currently handles about 70 percent of Maui Island's wastewater at three plants [44], each with a capacity of about 5 mgd [35]. Two of the three plants are capable of treating water to reusable, or R-1 standards, producing about 5.6 mgd of R-1 water and enabling reclamation of about 3 mgd as of 2010 [36]. The remaining 30% of wastewater that enters a

disposal system goes either to private treatment plants [36] or to cesspools and septic systems that do not treat the water [45].

HC&S, Maui's largest single water user, dominates agricultural water demand on Maui Island. HC&S self-supplies about 250 mgd, averaging 72 mgd as mildly brackish groundwater, 167 mgd as surface water from East Maui Irrigation, and around 7 mgd from Na Wai Eha (West Maui Irrigation) [42, 43], the most likely supply to be challenged by new instream flow requirements. HC&S purchases an additional 40–60 mgd of Na Wai Eha waters from Wailuku Water Company [43], for a total use of about 300 mgd. Once the water is on site, HC&S uses its own electricity supply to move the water through its fields. HC&S water does not require municipal treatment after use and thus does not incur additional energy costs for disposal, as any discharges are filtered and used for irrigation. While HC&S is the most significant agricultural water user, other agricultural uses account for almost as much water demand as the domestic sectors, at about 35 mgd. Most of this additional agricultural demand is surface water from streams in West Maui [46].

In addition to these domestic and agricultural supplies, industrial users pump almost 60 mgd of brackish groundwater to cool power plants and for other processes [4].

Finally, the dominant energy use for direct water services is also the most dispersed: end uses, primarily for water heating and on-site pumping for uses like swimming pools and landscaping, take place in homes, at hotels and resorts, and at commercial properties.

Water for energy

While most energy systems are dependent on water for fuel extraction and processing and for steam plant cooling (see e.g. [47]), Maui's reliance on imported fuels and air- or brackish water-cooled power plants means that its demand for local freshwater to support energy systems is comparatively low: that is, most of the water footprint of Maui's energy systems is embodied in imported fuels, not incurred on-island. It is well known that water is required for energy resource capture, particularly fossil fuel extraction and farming; for energy processing and conversion, particularly reservoir losses and refinery and thermoelectric power plant cooling; and for waste management, particularly flue gas desulfurization and land reclamation [48]. It is also well known that the location of water consumption or other use matters, as a water-rich area might be able to export embodied water in energy while a water-limited area might suffer disproportionately. This work contributes a spatially resolved assessment of local freshwater consumption for energy paired with an energy for water analysis, adding to the predominantly intensity factor-based

literature on water use for energy in such reports as [1, 48–51]. The remainder of this section introduces Maui's energy system and its water needs.

The local water that Maui does use for energy systems is mainly in the form of non-consumptive water for small in-line hydropower installations without reservoirs and for a 46 megawatt (MW) biomass-, waste-, and coal-fired power plant that consumes freshwater for cooling [37, 52, 53]. Maui's transportation sector consumes virtually no local freshwater, as oil products and ethanol are imported [7]. While Maui produces some biodiesel locally, it is produced in a dry process from waste products [54].

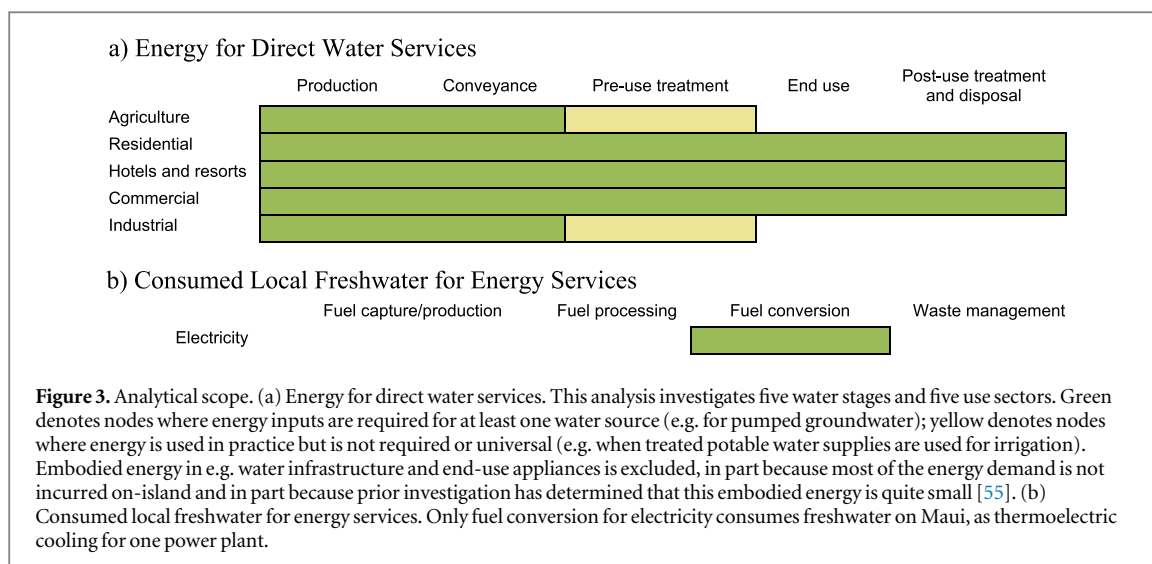
As Maui considers alternatives to oil for both cost and sustainability reasons, the island also considers different futures for its energy system's water intensity. While some renewable energy technologies (like wind and solar) would maintain the current low freshwater intensity, others (like biomass and biofuels) would dramatically increase dependence of the energy system on water by introducing local water needs for fuel capture and processing.

The electricity system is expected to undergo substantial changes in the near future, in part because of the potential early retirement of one of Maui's diesel power plants (Kahului Generating Station) [10] and the possibility of discontinuing a power purchase agreement for about a third of the output of the island's only freshwater-cooled power plant [8, 10]. Maui's existing renewable electricity plants demonstrate that depending on the chosen pathway, higher use of local resources for electricity production could either increase or basically eliminate water use for power generation. While state and county targets are likely to increase Maui's dependence on biofuels, particularly ethanol, it remains to be seen whether such fuels will be locally produced, with attendant freshwater use implications, or imported.

Methods and data sources

Assessing both the energy consumption for direct water services and the local freshwater consumption for energy services on Maui Island proceeds by first defining analytical boundaries (figure 3); defining water and energy flows and adjusting defined to the base year of 2010 as necessary (supplemental information, SI, available at stacks.iop.org/ERL/10/064009/mmedia); identifying nodes of energy or water use requirements for a given flow; then calculating an intensity factor (e.g. kWh mgal⁻¹; gal kWh⁻¹) or identifying one from the literature. Where possible, the bottom-up estimates based on flows and intensities are validated against top down values based on published data.

Energy consumption for water uses in the residential, tourism, non-tourism commercial, agricultural, and non-agricultural industrial sectors is assessed



along the life cycle stages of capture, conveyance, pre-use treatment, end use, and post-use treatment and disposal (figure 3(a)). Similarly, the analysis of local freshwater consumption for energy supply for electricity, transportation, and other heating along the life cycle stages of fuel capture, processing, conversion, and waste management (figure 3(b)).

Energy for water

Defining 2010 water flows on Maui Island proceeds by inventorying water uses and users and, where necessary, adjusting flows to account for use of a different base year via known ratios of 2010 values to other year values; excluding flows on other inhabited Maui County islands; and tracking wastewater and reclaimed water flows to avoid under- or overcounting. While significant information is available from a few key sources, this information is disaggregated by sector, source, and end-use; spread out over multiple years; available as proxies (e.g. in costs rather than energy); and organized with varying analytical boundaries [4, 11, 35–41]. Thus, this work required aggregation, organization and rectification of the data from disparate years to enable analysis, with assumptions detailed in SI. Maui's energy and water consumption has been stable (range of values spans about 10% of current use) for over a decade [39, 41], SI, which increases confidence in the use of linear scaling from recent non-2010 base years to 2010 where necessary.

Nodes of energy use requirements in the water system are identified based on interviews with Maui stakeholders conducted in 2011 and literature sources [36, 37, 55, 56]. Energy providers are also identified to enable conversion between electricity and primary energy consumption using the appropriate efficiency factor. These nodes are summarized in table 1.

Intensity factors are either calculated based on specific knowledge of a process or user or are identified in the literature. Factors and their sources are

summarized in tables 2 and 3. Derivations and other details can be found in SI.

Validation

After energy use by sector and lifecycle stage is calculated, values are compared with published data where available. Published data are generally either available as energy use numbers (e.g. in [55]) or as energy costs (e.g. in [56]). Data are adjusted to 2010 energy use numbers by scaling for 2010 populations, flows, and prices (accounting for the appropriate customer rate class) and to Maui Island-only numbers by scaling for Maui Island population and flows, accounting for the existence of different electricity rates on each of Maui County's islands. Details can be found in SI.

Water for energy

Maui's existing freshwater consumption for energy is limited to cooling at a single power plant, Central Power Plant at HC&S' Puunene Mill, and is estimated using Department of Energy averages for non-combined cycle thermal power plants with exhaust stacks and open-loop cooling, or 0.3 gal water kWh⁻¹ [48]. In 2010, the power plant produced about 170 GWh of electricity from bagasse (a fibrous sugarcane residue), coal, and some waste oils [3, 8].

No freshwater consumption is assigned to other power plants on Maui (small on-site and steam loop uses are considered negligible). The oil-fired units are cooled either by brackish groundwater (Maalaea, 212 MW and Kahului, 38 MW) [3, 58] or by air (Hana, 2 MW as diesel engines). Maui's wind generators consume no water, as is typical, and its hydro facilities are run-of-river units in irrigation ditches that do not require water impoundment that would foster power-related evaporation.

Additionally, no local freshwater consumption is assigned to fuel capture, processing, or other lifecycle stages on Maui, either for electricity generation or

Table 1. Water and energy sources by sectoral water user and locales of energy input. Water lifecycle stages requiring energy input for a given sector are labeled ‘yes’. Hotels and resorts are separated from other commercial uses due to the importance of the visitor industry on Maui: while hotels and resorts do not capture the full visitor industry (due to e.g. time shares and retail and restaurant activity), they provide a first approximation.

Sector	Water source	Energy source	Production	Conveyance	Pre-use treatment	End use	Post-use treatment and disposal
Residential	DWS	MECO for end use: MECO (55%), independent thermal (45%)	Yes	Yes	Yes—surface portion	Yes	Yes
Agriculture							
HC&S	Self-supply ground	HC&S	Yes	Yes—less reservoir losses			
	Self-supply surface	HC&S		Yes—less reservoir losses			
Kula Ag Park	DWS	MECO	Yes	Yes	Yes—surface portion		
East Maui	Rainfall	None					
Hotels and resorts	DWS	MECO	Yes	Yes	Yes—surface portion	Yes	Yes
	Self-supply ground	MECO	Yes	Yes		Yes	Yes
Industrial	DWS	MECO	Yes	Yes	Yes—surface portion	Yes	Yes
Other commercial	DWS	MECO	Yes	Yes	Yes—surface portion	Yes	Yes
Reclaimed post-treatment (multiple sectors)	Self-supply ground WWRFs	MECO MECO	Yes	Yes			

Table 2. Intensity factors used to calculate energy input for Maui Island direct water services. Flow-weighted intensity factors. Sources: HC&S, [37]; DWS production: 5 kWh kgal⁻¹ kft⁻¹, [6]; capacity-weighted depth of 686 feet, [42]; Self-supply groundwater pumping, US average, [24]; conveyance: US average, [1]; reclaimed water additional intensity after treatment for (uphill) conveyance from wastewater reclamation facility to end user, [25]; on site hotel/resort pumping for pools, landscaping, etc, assumed to be similar to reclaimed water pumping, usually used for landscaping; municipal wastewater treatment at 5 mgd plants, [23]; private wastewater treatment at small plants, [1, 23].

Sector	Water source	Production (kWh mgal ⁻¹)	Conveyance (kWh mgal ⁻¹)	Pre-use treatment (kWh mgal ⁻¹)	End use (kWh mgal ⁻¹)	Post-use treatment and disposal (kWh mgal ⁻¹)
Agriculture						
HC&S	Self-supply ground	1140	690			
	Self-supply surface		690			
Domestic and non-HC&S self-supply						
DWS	Ground	3430	300			3060
	Surface		300	1290		
Self-supply	Ground	1820	300			4640
Reclaimed or on-site hotel/resort pumping			980		980	

Table 3. Population-weighted factors. Sources: residential and hotels/resorts, [55], assuming 45% of residential hot water heating is thermal, with energy intensity converted to kWh-equivalents using MECO heat rate; commercial, [55, 57].

Sector	End use	Applies to?
Residential	930 kWh-e/person	Resident population
Hotels and resorts	1630 kWh/person	Visitor population
Commercial	150 kWh/person	De facto population

transportation fuels. Aside from wind, solar, and hydro energy, Maui's fuels, including ethanol, are imported and incur no local freshwater consumption. While HC&S does use milling wastewater to irrigate about 360 acres of sugarcane that is used only for power production due to low cane quality, this use is explicitly as a means of disposing industrial wastewater with high organic content and thus is not considered a consumptive use of freshwater for energy [59].

Results

Energy for water

Maui used an estimated 5000 TJ (4700 billion btu, 440 GWh-e equivalent) of primary energy for direct water services in 2010, including about 430 GWh of electricity, 10 billion btu of propane, and 45 billion btu of solar thermal energy for water heating (table 4). Benchmark energy consumption data comprise three sources: Maui Electric Company (MECO) and private generation data for electricity, and per-capita Hawaiian primary energy use to capture non-electric demand [3, 8, 11]. Overall, energy for direct water services accounts for 32% of Maui Island's electricity consumption and 19% of Maui Island's on-island primary energy. By sector, residential uses account for 39% of primary energy for direct water services, followed by agriculture at 26%. By lifecycle stage, end uses account for 51% of primary energy for direct water services such as heating, followed by groundwater pumping at 26% (figure 4).

Table 5 shows the results of comparing intensity-based bottom-up estimates with published top-down estimates for energy use for direct water services. Details can be found in SI.

Water for energy

While Maui's energy consumption for water is significant, its water consumption for energy is relatively trivial. Maui consumed an estimated 0.14 mgd of local freshwater in 2010 for energy, entirely as cooling water at HC&S' Central Power Plant. This consumption translates to 0.05% of Maui's daily freshwater consumption of about 300 mgd.

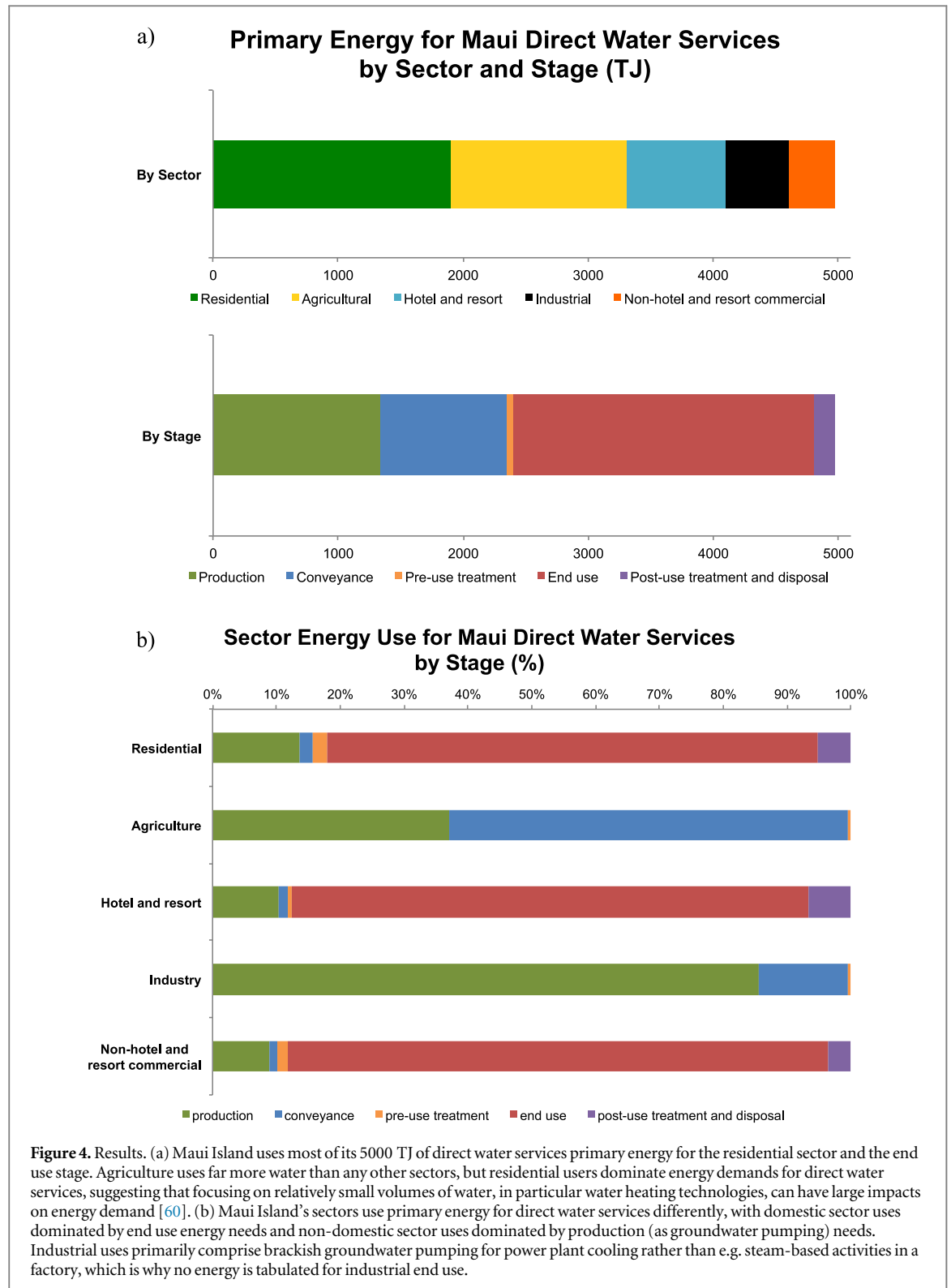
Table 4. Results (2010 base year). Residential uses are the largest uses of primary energy for direct water services on Maui. All energy use for water systems is electrical except for some residential water heating, which is given as GWh-equivalent. Conveyance intensities are applied to all DWS and private water that reaches an end user but not to water that is lost before it is conveyed at HC&S fields. 'No use' is denoted '—', while '0' indicates small consumption (<0.5 GWh or <0.5 TJ). Total primary energy for Maui excludes aviation energy: see SI for details.

	Volume (mgd)	Electricity (GWh-equivalents)	Primary energy (TJ)
Residential	30	175	1900
DWS			
Groundwater	19	126	1365
Surface water	8.0	48	519
Parks and landscaping			
Groundwater	1.0	1	8
Reclaimed water	2.1	1	8
Agriculture	339	116	1407
HC&S			
Groundwater	85	57	701
Surface water	219	47	581
Na Wai Eha Kuleana			
Surface water	6.8	—	—
DWS			
Groundwater	2.6	4	38
Surface water	1.1	1	7
Private			
Groundwater	7	5	59
Surface water	17	2	20
Reclaimed water	0.2	0	1
Hotel and resort	10	73	795
DWS			
Groundwater	2.3	17	185
Surface water	1.0	7	71
Private			
Groundwater	7	50	538
Industry	61	47	512
DWS			
Groundwater	1.1	1	16
Surface water	0.5	0	3
Private			
Groundwater	59	45	492
Reclaimed water	0.5	0	2
Non-hotel and resort commercial	4	34	364
DWS			
Groundwater	2.4	24	260
Surface water	1.0	10	103
Reclaimed water	0.1	0	0
Water-related subtotal	443	445	4977
Maui on-island total	443	1387	26 677
Water-related percent of total		32%	19%

Discussion

Current uses of energy for water

Maui Island uses more energy for direct water services than most other United States systems, at around 19% of its on-island primary energy demand versus a



national average of 8% [17]. The biggest energy demand is associated with the use phase, consistent with other reports in the literature [17, 21, 61]. In primary energy terms, Maui is quite similar to California, which uses about 15% of its primary energy for water and, in part due to its similar mountainous terrain and large agricultural economy, is known for large energy demand for water systems. However, while California uses about 19% of its electricity for water [21], Maui uses 32%. A large driver of this

difference is Maui's relatively extreme dependence on electricity given a lack of access to natural gas, a more typical water heating fuel [62].

Changes to Maui's grid will not directly affect the primary energy demand for direct water services, but they could alter the implications of the energy use. Specifically, since Maui's grid is dominated by oil-fired electricity, the water system's electricity requirements contribute to high costs, import dependence, and contributions to climate change. LNG imports together

Table 5. Validation results. Intensity-based estimates of energy use for Maui's water systems are compared to population- and water demand-adjusted top-down estimates of energy use for particular aspects of the water system as available. Further details of analysis can be found in SI.

(a) County (DWS and Environmental Management, Maui Island) energy use validation. Details in SI. Sources: [39–41, 56]				
User	2006 Use (GWh)	Adjusted 2010 Use (GWh)	Intensity-based estimate (GWh)	% Difference
DWS	45.8	43.4	43.0	−1%
Environmental management	22.9	22.9	19.2	−16%
Total	68.7	66.3	62.2	−6%

(b) HC&S energy use validation. Details in SI. Sources: [3, 8]			
User	2010 Self-generation (GWh)	Intensity-based estimate (GWh)	% Difference
HC&S self-generated use	122	104	−15%

(c) MECO energy use validation for residential/commercial end uses and visitor industry end uses. Details in SI. Source: [55]				
Sector	2004 Use (GWh)	2010 Adjusted use (GWh)	Intensity-based estimate (GWh)	% Difference
Residential electric water heating	83.4	93.5	73.9	−21%
Non-hotel commercial electric water heating	8.3	9.0	28.4	214%
Residential and non-hotel/resort subtotal	91.7	102.5	102.3	0%
Hotel and resort miscellaneous use	59.5	58.8		
Hotel and resort commercial use	7	6.9		
Hotel and resort subtotal	66.5	65.8	59.3	−10%
End use total	158	169	162	−4%

with distribution infrastructure investments could enable more use of thermal energy for water heating (which on life-cycle is more efficient than electrical heating) and potentially supply lower-carbon, lower cost electricity. Maui is already pursuing greater use of renewable energy, both as electricity and solar thermal water heating. One disadvantage of Maui's major renewable resources, wind and solar, is intermittency: a potential synergy with the energy-intensive water system might be to use groundwater pumping as a demand response mechanism. For example, investing in variable speed drive pumps that are able to adjust pumping rates and turn on and off relatively efficiently could support grid operations on Maui's small system, whether through ancillary services like power factor correction (see e.g. [63]) or simply by enabling operators to run pumps when energy is available and turn them down when energy is more constrained, perhaps by coupling systems like desalination and intermittent renewable energy [64, 65].

Current uses of water for energy

Maui Island uses far less water for its energy systems than most other jurisdictions, in large part due to its use of brackish water and air for power plant cooling and to its use of imported fuels. Maui's energy systems are currently basically independent of its water

systems, which is an unusual condition. A shift toward more on-island resource use in the form of biofuels could increase this dependence, while a shift toward wind, solar, or geothermal would preserve this independence.

Future demands on Maui's energy and water systems

Maui's water system is likely to get more energy intensive in the future without significant declines in demand for fresh, gravity-fed, low energy-intensity surface water for irrigation or investments in water conservation. Currently, Maui residents use significantly more freshwater per capita than other Americans, who in turn use significantly more freshwater per capita than the global average [32]. Focusing on conservation and urban metabolism-guided planning could alleviate some concerns about water allocations, particularly in more urbanized areas [67], but growing demand for groundwater connections in rural Upcountry Maui and other isolated areas will likely continue to put pressure on energy systems. Developing additional groundwater supplies from distant or deep aquifers will require energy for pumping [59], and Maui is likely to use more energy for water treatment in the future to address water quality

concerns and to increase freshwater availability through reuse or even desalination.

Concerns about nutrient-rich wastewater from cesspools [45] and wastewater treatment plants [66] reaching the ocean and affecting marine and human health are likely to lead to additional wastewater treatment demands. Adding UV disinfection to the roughly 50% of county-handled wastewater not currently treated with UV would increase energy demand by about 1.9 GWh yr⁻¹, 6% of current municipal wastewater treatment energy demand. Increasing treatment standards at county facilities to further reduce coliform counts could increase ultraviolet disinfection's energy demand from about 340–1000 kWh mgal⁻¹ [23], corresponding to an additional 8.8 GWh yr⁻¹ to treat all County-handled wastewater, or 27% of current municipal wastewater treatment energy demand (<1% of whole-island demand). At either level, UV-treated water can be used for non-potable water needs.

Desalination is another form of energy intensive water treatment that Maui could pursue to increase access to fresh water. Desalination could add freshwater supplies with energy demands of 4900 kWh mgal⁻¹ (brackish groundwater, [6]) to 16 000 kWh mgal⁻¹ (seawater, [6]). Supplying 10% of Maui's 2010 demand for municipal potable water with brackish desalinated water would require an estimated additional 5.9 GWh yr⁻¹ for treatment, about 14% of current DWS demand (<1% of whole-island demand). The energy demand grows to 19 GWh yr⁻¹ for the same amount of seawater desalination, about 45% of current DWS demand (1.5% of whole-island demand). Unlike wastewater treatment for reuse, desalination does not provide other environmental co-benefits: rather, desalination would create a new waste product that would need to be addressed, namely desalination brine [68]. Thus, while additional sources of water are clearly available given enough energy or capital investment in conservation, the energy demands and other infrastructural needs to develop these waters are high.

The most explored transportation energy transition for Maui and the State of Hawaii is a shift from imported petroleum-based fuels to locally grown biomass-based fuels, specifically ethanol. Were Maui to embrace a transition from sugarcane for sugar cultivation to sugarcane (or another crop) for ethanol production, the island could potentially produce enough ethanol to supply the entire State's ethanol demand under State mandates, or about 80–90 mgal yr⁻¹ by 2020 [69–71]. Converting Maui's entire sugarcane crop from a sugar-for-export crop to a sugar-for-ethanol crop could produce 100–200 mgal yr⁻¹ without increasing total freshwater demand [71], implying that the state's full ethanol demand could be met without exhausting Maui's agricultural land and water resources. Despite limited impact on overall freshwater demand, a strong commitment to on-island biofuels would substantially increase Maui's (and

potentially Hawaii's) energy systems' dependence on variable and contested water supplies. Maui currently uses about 60% of its freshwater for sugarcane agriculture, which makes this use particularly susceptible to both natural and political changes in freshwater availability: while a shift to biofuels would not affect water allocation or demand significantly versus current conditions, it would make the energy system much more dependent on continued surface water abundance and allocation to agriculture than it is now.

Conclusions

Maui Island uses about 19% of its on-island primary energy for direct water services, which is much higher than the US average of 8% [17]. As Maui seeks to expand its freshwater supplies (particularly in rural areas) and protect its coastal waters with stricter wastewater treatment, this value could increase with additional groundwater pumping, desalination, and increased treatment intensity. However, were surface irrigation waters to become available due to a changing agricultural landscape, energy intensities for the water system could also decline, as surface water is transported from Maui's high elevation streams to lower elevation population centers largely by gravity.

In turn, Maui Island consumes only about 0.05% of its freshwater to support its heavily import-based energy systems, much lower than the US average of over 6% (including thermoelectric cooling consumption, biofeedstock irrigation, and oil and natural gas extraction) [47]. Converting Maui's sugar crop from a food supply to an energy supply in the form of biofuels to displace petroleum would make Maui's energy system much more dependent on freshwater, as about 60% of Maui's freshwater is consumed for sugarcane irrigation and is subject to drought and uncertain future allocation. Maui's energy future will also affect its freshwater systems indirectly by changing cost structures: since Maui's freshwater supplies are limited by cost effective electricity supplies, a shift that leads to lower electricity prices than the existing petroleum-linked prices could actually increase freshwater supplies on the island, and vice versa.

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