

PET bottle reverse logistics—environmental performance of California's CRV program

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Abstract

Purpose Disposable beverage bottles made of polyethylene terephthalate (PET) stand in sharp contrast to many other disposable plastic packaging systems in the US for their high level of post-consumer recovery for recycling. This is due in part to container deposit programs in several US states, such as the California Redemption Value (CRV) program. We investigate the impacts of PET bottle recycling in the CRV program to evaluate its effectiveness at reducing environmental burdens.

Methods We develop a life cycle model using standard process LCA techniques. We use the US LCI database to describe the energy production infrastructure and the production of primary materials. We describe the inventory and logistical requirements for materials recovery on the basis of state-maintained statistics and interviews with operators and industry representatives. We report inventory indicators describing energy, freight, and waste disposal requirements. We report several impact indicators based on CML and TRACI-2.0 techniques. We apply system expansion to compare post-consumer activities to produce secondary polymer against equivalent primary production.

Results and discussion While bottle collection is distributed across the state, processing is more centralized and occurs primarily near urban centers. The average distance traveled by a bottle from discard to recovery is 145–175 km. Recycling requires 0.45–0.66 MJ of primary energy/L of

beverage, versus 3.96 MJ during the pre-consumer phase. Post-consumer environmental impacts are significantly lower than pre-consumer impacts, with the exception of eutrophication. The results are robust to model sensitivity, with allocation of fuel for bottle collection being the most significant parameter. Curbside collection is slightly more energy efficient than consumer drop-off, and is subject to smaller parametric uncertainty. Recycling has the potential for net environmental benefits in five of seven impact categories, the exceptions being smog (marginal benefits) and eutrophication (increased impacts).

Conclusions California's decentralized program for collecting and processing PET bottles has produced a system which generates a large stream of post-consumer material with minimal environmental impact. The selection of a reclamation locale is the most significant factor influencing post-consumer impacts. If secondary PET displaces primary material, several environmental burdens can be reduced.

Recommendations and perspectives Our results suggest that deposit programs on disposable packaging are an effective policy mechanism to increase material recovery and reduce environmental burdens. Deposit programs for other packaging systems should be considered.

Keywords California Redemption Value · CRV deposit program · Curbside recycling · Materials recovery · PET bottles · Reverse logistics

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1 Introduction

Thermoplastic polymers are widely used in the production of disposable plastic packaging, most of which is not collected for recycling. A prominent exception is the single-use beverage bottle made of polyethylene terephthalate (PET). PET bottles are the most abundantly recycled plastic product

in the US (US Environmental Protection Agency 2010). Over 650,000 tonnes of PET bottles were recycled in 2009, accounting for 28 % of bottles sold (National Association for PET Container Resources 2010). About 45 % of those bottles were purchased by reclaimers in the US who used them to produce secondary PET polymer (R-PET); the remainder was exported to reclaimers overseas (*ibid.*). R-PET is used widely in textiles and in rigid packaging applications, including new PET bottles (Kuczenski and Geyer 2010).

The US post-consumer PET bottle stream is supported significantly by beverage container deposit programs such as the California Redemption Value (CRV) program. The CRV program applies a 5-cent deposit to all covered beverage containers below 24 oz (680 mL) and a 10-cent deposit to larger containers. The deposit is redeemed by returning the bottle for recycling. California's program recovered 73 % of the bottles sold in-state in 2009, and the recovery rate has steadily increased over time (Brown 2010). Although California contains only 12 % of the US population, California collections represent 25 % of US post-consumer PET. California's CRV program is distinct among ten similar programs in US states in two important ways.¹ First, it allows for deposits to be redeemed in bulk on a weight basis; and second, deposits to the program are held by the state in a unitary fund, allowing refunds to be reimbursed uniformly for all bottles regardless of manufacturer (Berck and Goldman 2003). Unclaimed deposits revert to the state and are used to fund program administration and demand-side market development.

The CRV program establishes a two-step system of "collection" and "processing" for bottle recovery, which is maintained through a certification and reporting framework (California Code of Regulations, Title 14, Division 2, Chapter 5). Collection from consumers is performed by certified operators known as "recyclers," which include municipal, commercial, and non-profit organizations. The recyclers then sell the empty bottles to "processors," who are responsible for canceling the redemption value of the bottles. A single operator can be certified for both collection and processing. The agency recognizes four collection modes: drop-off recycling centers; curbside programs servicing residential addresses; commercial collection programs; and volunteer or non-profit community service programs. Only recycling centers provide consumers with a means to recoup their deposits; in other systems the deposit money goes to the organization performing the collection (CalRecycle 2011a).

Recycling of plastic waste can reduce resource demand and environmental impacts by displacing the production of

primary material. R-PET is widely used in the manufacture of similar product systems to primary PET, notably textiles, as well as beverage bottles and other rigid packaging (Kuczenski and Geyer 2010), although technical restrictions may prevent the use of R-PET as a drop-in replacement for primary polymer (Shen et al. 2010). When secondary PET is selected in place of primary PET, the net environmental effect of using secondary material depends on the difference in burdens between primary and secondary production.

In this paper, we characterize the environmental burdens that result from a PET bottle in the CRV program being collected and recycled. Our study has two objectives. First, we compare the three main end-of-life pathways followed by CRV PET bottles: landfilling, curbside collection, and consumer drop-off. This comparison is intended to aid consumers and policymakers in decision making about PET bottle waste, and to demonstrate the relative contributions of the reverse logistics and reclamation stages. Second, we evaluate the potential environmental improvement that could be obtained through PET recycling by comparing the impacts of secondary production against those of equivalent primary production. In order to estimate an upper bound for this improvement, we develop a scenario favorable to R-PET in which post-consumer bottles are mechanically recycled into a material that directly displaces primary PET. We employ system expansion to compare this scenario against the avoided scenario of landfilling the bottle and producing primary PET.

2 Methods

2.1 Functional unit

We model the delivery of 1 L of beverage to a California consumer in single-use PET bottles during the years 2007–2009. The polymer required per functional unit is estimated based on a simplified model of the California beverage market as comprising 60 % bottled water, 16 % carbonated soft drinks, and 24 % juice/sports and other drinks (Anonymous 2006; Beverage Digest 2008). This market model, combined with direct measurement of typical beverage products, leads to an assumption of 35.8 g of PET polymer required/L of beverage, plus 5.0 g of polypropylene (PP) polymer/L for closures and labels. For consistency with the system expansion method, we assume bottles, caps and labels are made entirely of primary material.

Figure 1 shows a diagram of our process flow model. The default path for (non-recycled) PET bottles is to be collected as municipal solid waste and deposited in landfill. The post-consumer handling of the bottles that are recycled is divided into the stages of reverse logistics and reclamation, with reverse logistics being further broken down into the "hand

¹ Hawaii's program is modeled after California's and has similar characteristics.

to bale” and “bale to reclaimer” portions. These process steps are discussed further in Section 2.4.

Polypropylene caps are assumed to be predominantly discarded by the consumer or not collected at the hand-to-bale stage. This is consistent with operator interviews as well as published guidance on the CalRecycle website (CalRecycle 2011b). Caps and labels that do reach the reclamation stage are separated and reclaimed for use. This stream measures approximately 0.85 g secondary PP/functional unit. No environmental benefit is attributed to this material stream.

2.2 Indicators

We report several inventory and impact indicators for each life cycle stage. Inventory indicators include primary energy demand (net calorific value or ncv), energy of transport fuel, freight service demand, and solid waste generation. Energy of transport fuel is the net calorific value of fossil fuel products or electricity consumed by transport systems including cars, trucks, trains, pipelines, barges and ocean freighters. This indicator excludes upstream energy expended in the fuel cycle and in electricity production and reports only energy consumed directly by a transport mechanism. Freight service demand is defined as the product of payload mass and transport distance, summed over all transport systems in a stage. The freight service demand indicator includes fuel cycle and supply chain freight. Solid waste generation measures the total mass delivered to a terminal solid waste management process, including landfill and incineration. This indicator also includes fuel cycle waste.

Impact indicators are taken from the Leiden Institute for Environmental Studies (CML) indicator family (Guinée et al. 2002) and the Tool for the Reduction and Assessment of Chemical and other Impacts (TRACI), version 2.0 (Bare 2011). They include (CML indicators) global warming potential, acidification potential, eutrophication potential, and photochemical ozone creation potential; and (TRACI indicators) eutrophication potential, smog creation potential, and criteria pollutants. Toxicity indicators were omitted due to large inconsistencies in inventory reporting and impact category results among multiple data sources.

2.3 Data sources

2.3.1 Core model: US LCI database

Inventory data for the energy cycle, including fossil fuel extraction, fuel refining, combustion, electricity production, and freight transportation, were taken from the US Life Cycle Inventory (US LCI) database (US LCI 2011). The US LCI database also includes inventory for PET resin

primary production and reclamation of post-consumer PET (Franklin Associates 2007, 2010). The power grid mix was modeled according to the EPA eGrid database (US Environmental Protection Agency 2009). We modeled the US average grid mix as well as the production mix of the Western Electricity Coordinating Council (WECC), which includes California. We used the US average mix for the cradle-to-polymer and reclamation stages, and the WECC mix for the other life cycle stages assumed to occur in California.

In adopting the US LCI database as the core of our life cycle model, we also adopted its inherent system boundary and other modeling decisions. The US LCI database processes we used omit infrastructure, capital equipment production and disposal, operations, vehicle and machinery maintenance, overhead, land use, and water use. The system boundary in our model can be regarded as “tight-fitting,” including direct process emissions and energy supply but omitting many environmental impacts from upstream supply chains, such as chemical additives, dyes and adhesives, and secondary packaging of bottles. This information is omitted due to lack of data. According to a recent study, the inclusion of secondary packaging would increase energy demand by about 15 % and solid waste generation by about 20 % (Franklin Associates 2009).

Several key processes that fall within this tight boundary are nonetheless not available in the US LCI database. We used cradle-to-gate process inventories from the Ecoinvent 2.01 database (Frischknecht et al. 2007) for important supply chain and end-of-life processes, including production of baling wire; sodium hydroxide; lubricating oil; disposal and incineration of solid waste and refinery sludge; and hydroelectric power. Plastic forming processes were modeled based on a review of literature. The injection and stretch blow molding process was estimated to require 1.8 kWh of electrical energy/kg of PET output (Hischier 2007; Boustead 2005; Gleick and Cooley 2009). Table 1 shows inventory and impact indicator results for several important unit processes used in the model.

2.3.2 Heavy truck transport

Within the US LCI database, unit process data for heavy truck transportation are based on unpublished modeling by Franklin Associates (US LCI; dataset for US: Transport, combination truck, diesel powered; 2011). Because truck transport was expected to be a major component of reverse logistics, we desired a process inventory model that was demonstrably consistent with California conditions. We developed an emission inventory for heavy truck travel in California based on the Motor Vehicle Emission Inventory Model (EMFAC) developed by the California Air Resources Board (California Air Resources Board 2006).

Reverse Logistics Detail

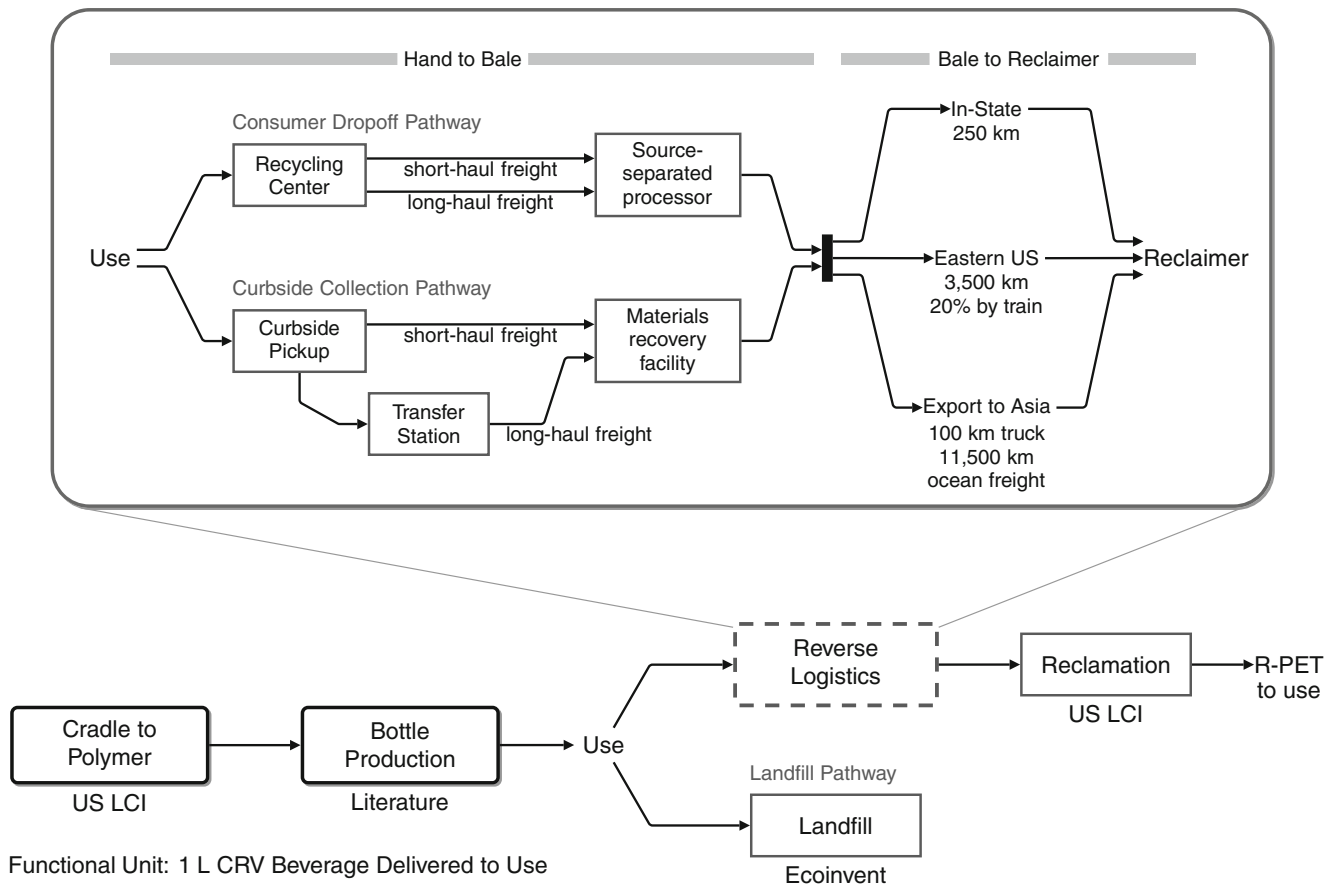


Fig. 1 Process flow diagram for the PET bottle system

The EMFAC tool implements an aggregate inventory estimate of the total resource requirements and environmental emission burdens resulting from vehicle transportation in California. The tool combines a description of the total size of the vehicle fleet in California with tailpipe emission measurements and technical models of road travel to generate estimates of aggregate fuel use and environmental emissions. We combined EMFAC data with our own estimates of vehicle payload and backhaul to estimate unit process inventories for various classes of truck transportation. The details of our model are provided in the [Electronic Supplementary Material](#). We found heavy truck transportation to require 0.037 kg of diesel fuel/tonne-kilometer, assuming an average payload of 14.3 tonnes and a backhaul ratio of 30 % (i.e. 30 % of vehicle miles are traveled empty). The EMFAC-derived model was deemed to be the most appropriate inventory for US truck transport, and was used throughout the study.

Waste collection vehicles were modeled after heavy diesel equipment to reflect fuel expenditures during idle and compacting operations. We used the US LCI process for “Diesel, combusted in equipment”, modified to reflect California and federal emission standards. Modifications

included the reduction of particulate matter emissions by 75 % and adjustment of sulfur dioxide emissions to reflect ultra-low-sulfur diesel fuel standards (California Air Resources Board 2007a, b). The unit process impacts of our truck transport processes are shown in Table 1.

2.3.3 PET bottle reverse logistics

Figure 1 shows a process flow diagram of our recycling model, which includes three sequential stages. The “Hand to Bale” stage spans the entire CRV program. It begins with the empty bottle after the point of use and comprises the two steps of collection and processing. The two steps are linked by a logistics step representing transport from collection to processing. The processing step ends with the bottle being incorporated into a bale of post-consumer PET, at which point the bottle is considered to be “recovered” and the deposit may be redeemed from the state. Industry resources describing typical bale conditions are available (Association of Postconsumer Plastics Recyclers 2011). The typical bale modeled in our study weighs around 0.3–0.5 t, corresponding to roughly 12,000–22,000 bottles, and occupies 1–1.3 m³ of volume. Baling requires around 0.13 kWh

Table 1 Inventory and impact data for key unit processes

Unit process		Electricity at Grid, US 1 kWh	Electricity at Grid, WECC 1 kWh	Diesel, waste collection vehicle 1 L	Heavy truck 1 tkm	Train 1 tkm	Ocean freight 1 tkm	PET Resin cradle-to-gate 1 kg	PET Resin to landfill 1 kg
Output									
Source		US LCI + eGrid	US LCI + eGrid	US LCI/CARB	EMFAC	US LCI	US LCI	US LCI	Ecoinvent
Primary energy demand	MJ _{gev}	11.0	9.9	45.9	2.02	0.30	0.24	72.1	0.33
	MJ _{nev}	10.4	9.4	42.9	1.89	0.28	0.23	66.7	0.31
Energy delivered to process	Renewable MJ _{nev}	0.45	1.23	–	–	–	–	0.42	–
	MJ _{nev}	3.6	3.6	–	–	–	–	20.2	–
Energy of transport fuel	MJ _{nev}	–	–	37.0	1.63	0.24	0.20	1.58	–
Freight required	kgkm	457	350	5,090	224	32.7	26.8	7,200	–
Waste disposal required	g	44	23	38	1.7	0.25	0.20	93.0	–
Global warming ^a	g CO ₂ -eq	792	598	3,200	139	22	19	2,550	80
Acidification ^a	g SO ₂ -eq	7.4	5.6	32.9	0.90	0.30	0.30	27.1	0.093
Eutrophication ^a	mg P-eq	268	177	7,350	182	68	59	1,030	120
Eutrophication ^b	mg N-eq	104	72	2,660	69	24	21	714	210
Photochem. ozone ^a	mg C ₂ H ₄ -eq	735	601	3,710	138	31	27	5,060	27.0
Smog ^b	g O ₃ -eq	53.1	35.5	1,390	33.7	12.8	11.1	162	2.6
Ozone depletion ^a	ng R11-eq	97	113	243	10.70	1.57	1.29	1,640	3,100
Criteria pollutants ^b	g PM10-eq	0.99	0.77	3.0	0.16	0.04	0.04	3.90	0.03

^a From CML 2001 Impact Indicators, November 2009 Revision^b From TRACI-2.0 Impact Indicators

of electricity and approximately 16 m of steel baling wire/bale, based on a review of product literature and specifications as well as direct observation. The “Bale to Reclaimer” stage covers the logistics of transporting the bale from processing to a reclamation facility. Finally, the reclamation stage includes the conversion of bales into R-PET pellets.

2.4 Hand-to-bale stage—modeling details

Process inventory details for the hand-to-bale stage were developed through telephone interviews and surveys of program operators throughout the state, and supplemented with facility tours of recycling and processing facilities in the California counties of Santa Barbara and Ventura. The survey methodology was to identify aggregate measures over the broadest possible time periods, including total material collected or processed, and compare it to measures of total energy and fuel consumed over the same period. Process inventories were limited to the following energy sources: propane (liquefied petroleum gas), diesel, natural gas, and electricity. Over fifty operators were contacted, with approximately half providing quantitative information. Most data points are supported by three to five responses, with exceptions noted. An example survey instrument can be found in the [Electronic Supplementary Material](#).

We model two distinct hand-to-bale pathways, “Consumer Drop-off” and “Curbside Collection”. Each pathway includes a collection step, collection-to-processing logistics, and a processing step, which we describe in detail below. Table 2 shows the parameter values used in modeling the hand-to-bale stage. These values represent our estimates of typical resource requirements. With the exception of fuel usage for curbside collection ($n=7$), no data point represents a large enough sample to support a statistical error estimate. Individual data samples are confidential and are not disclosed.

2.4.1 Consumer drop-off pathway

California law requires that there must be a recycling center located within a 0.8 km (0.5 mi) “convenience zone” of most full-service supermarkets meeting a minimum annual sales threshold. In practice, many recycling centers are located in the parking lots of supermarkets. These centers are generally unpowered or minimally powered attended facilities where customers drop-off sorted bottles in exchange for a receipt that can be redeemed in the store.

We modeled the consumer drop-off pathway as delivery of empty bottles by the consumer to a recycling center. We developed a consumer vehicle transport model based on the GREET tool version 1.8c (Argonne National Laboratory 2010). We assume a consumer drop-off involves a 1.6-km round trip to a recycling center in a US-typical vehicle (fuel

economy 10 L gasoline/100 km), and that the trip results in the delivery of 4 kg of source-separated recyclables, including 1 kg of PET. This amounts to one 1.6-km vehicle trip/kg of PET delivered, with 25 % of the trip allocated to PET delivery. This value was determined as a placeholder based on observation, noting that the size of drop-off payloads, the distance traveled, and the means of transportation are all likely to be widely varied. We discuss the sensitivity to this modeling decision in Section 3.4 below.

After collection, bottles are transported in bulk to processing facilities, where they are compacted into bales. At these facilities, containers made of different materials arrive already sorted, and all that remains is for PET bottles to be compacted into bales for shipment to reclaimers. Source-separated processors were modeled as requiring electricity for facility operation and baling, propane for powering forklifts, and baling wire.

2.4.2 Curbside collection pathway

In the curbside collection pathway, private operators are assumed to operate fleets of trucks which make periodic visits to subscribers’ homes and businesses, collecting commingled recyclables. Although the average transport distance is small, most of the environmental impacts come from the operation of collection vehicles which spend a large portion of their routes at idle or at low speeds, using the engine to operate lifts or compactors. Our model related fleet fuel use to total commingled collection by mass. We also assumed a yield loss to account for the collection of non-recycled material, which requires fuel to collect but is not baled. We obtained detailed survey results from 11 curbside operators in nine California counties, including both urban and rural areas, with truck fleet sizes ranging from a single vehicle to 115 vehicles. Seven of those responses included fuel usage and were used to compute the fuel requirements per tonne of curbside collection. All curbside collection was modeled as single-stream (i.e. paper products mixed with containers).

Processing in the curbside collection pathway involves sorting commingled recyclables into distinct materials in a materials recovery facility (MRF). Curbside collection vehicles were assumed to deliver commingled recyclables either directly to a MRF, or to a transfer station where they were loaded onto long-haul trucks and then brought to a MRF. Both MRFs and transfer stations were modeled as requiring diesel fuel for the operation of heavy loaders to handle commingled recyclables. MRFs additionally required electricity to operate sorting equipment and baling machines, propane for powering forklifts to handle baled recyclable materials, and baling wire. We used mass-based allocation to describe MRF resource requirements. It was challenging to obtain MRF and transfer station data, and each

Table 2 Important inventory parameters

Parameter	Value	Units	Description and sources
PET containers			
PET polymer required per L	35.8	g	Measurement; beverage market modeling
PP polymer (cap and label) per L	5.	g	Measurement; beverage market modeling
Beverage production			
Stretch blow molding electricity	1.8	kWh/kg PET	Boustead (2005); Gleick and Cooley (2009)
Hand to bale			
Diesel fuel, waste to municipal landfill	18	L/t waste	Estimate
Diesel fuel, curbside collection	21±12	L/t	Operator Surveys
Recyclable material yield, curbside + MRF	85 %	–	Operator Surveys
Diesel fuel, MRF + transfer station	0.75	L/t	Operator Surveys; Chester et al. (2008)
LP gas, source-separated processor	1	L/t	Operator Surveys
LP gas, MRF/processor	7	L/t	Operator Surveys; US LCI
Electricity, source-separated processor	1.5	kWh/t	Operator Surveys
Electricity, MRF	16	kWh/t	Operator Surveys; Chester et al. (2008); US LCI
PET baling electricity	0.13	kWh/bale	Review of baling machinery; 400 kg bale
Baling wire, 10 AWG	16	m/bale	Estimate; 1.2 m ³ bale
Transport distances			
PET resin to bottling	3,500	km	Estimate
Beverage distribution	72	km	2002 Commodity Flow Survey, code 078
Collection-to-processing, in-county	31	km	Geographic modeling
Collection-to-processing, long-haul	350	km	Geographic modeling
Processing to in-state reclaimer	250	km	Estimate based on CalRecycle (2009)
Processing to out-of-state reclaimer	3,500	km	Estimate

data point for these facilities is based on responses from only one or two facilities. To improve the accuracy of our inventory requirements, we compared our results to values published in the literature (Chester et al. 2008; Franklin Associates 2010) and available in the US LCI database. The inventory requirements used in our model were comparable in magnitude to these sources.

2.4.3 Hand-to-bale logistics

Collection-to-processing logistics are modeled based on data provided by CalRecycle, the state agency responsible for administering the CRV program. CalRecycle provided us with data on the volume of PET collected and processed in each county on an annual basis over the period from 2001 to 2009. In order to estimate the collection-to-processing distance, we compared the volume of PET collected to the volume of PET processed in each county. Counties whose reported processing volume exceeded their reported collection volume by 2 % or more were denoted “surplus” counties and were assumed to process bottles collected in other counties.

We then divided each county’s PET collections into a portion that was processed locally and a remainder that was processed in surplus counties. Counties with a processing deficit were assumed to first process locally-collected PET

up to their reported processing volume, and then ship the remainder to the surplus counties in amounts proportionate to each destination county’s share of total surplus volume. We computed in-county and out-of-county “long-haul” transport distances for each county and then found a volume-weighted statewide average transport distance for each segment. The average transport distances for in-county and long-haul distances are shown in Table 2.

The portion of bottles that were transported to another county for processing was denoted the “long haul fraction.” In the consumer drop-off pathway, bottles were assumed to travel either the in-county distance or the long-haul distance, depending on where they were being processed. In the curbside collection pathway, all bottles were transported the in-county distance by the curbside collection vehicle, and then only the out-of-county fraction was transported the additional long-haul distance.

2.5 Bale-to-reclaimer stage and reclamation

We modeled three destinations for bales of post-consumer PET bottles based on information about the existing post-consumer PET market in California (CalRecycle 2009; National Association for PET Container Resources 2010). The destinations include: an in-state reclamation facility (250 km

by combination truck); an out-of-state domestic reclaimer located in the Eastern US (3,500 km, 20 % by train, 80 % by combination truck; see Franklin Associates 2010); and an East Asian port (100 km combination truck, followed by 11,500 km ocean freighter). The reclamation process is modeled under California conditions (using the WECC electrical grid) regardless of bale-to-reclaimer route in order to isolate the contributions of logistics.

2.6 Primary versus secondary production

Several methodological approaches have been devised to compute the net impacts of recycling in life cycle assessment (Ekvall and Tillman 1997; Ekvall and Weidema 2004; Shen et al. 2010). The system expansion method permits the comparison of two systems with equivalent inputs and outputs. We employ system expansion to compare mechanical recycling of CRV bottles to R-PET pellets against landfilling of bottles plus primary production of an equivalent amount of PET pellets (Fig. 2). We report our comparison as a ratio of burdens from recycling to burdens avoided by recycling, rendering the results independent of a functional unit. We measure the potential improvement as follows:

$$f = \frac{B_{\text{recycling}}}{B_{\text{avoided}}} = \frac{B_{\text{reverse-logistics}} + y \cdot B_{\text{reclamation}}}{B_{\text{landfill}} + y \cdot B_{\text{displaced-primary-polymer}}} \quad (1)$$

where burdens B are expressed on a unit output basis (except landfill, which is unit input), and y is the yield of the PET reclamation process, which we take to be 0.8 (Franklin Associates 2010). Here we assume R-PET is equivalent to bottle grade primary PET, and so $B_{\text{displaced-primary-polymer}}$ is equivalent to the cradle-to-polymer stage in Fig. 1. This represents an optimistic assumption and establishes an upper bound for the improvement that can be attributed to recycling. If the resulting fraction f is less than 1, the secondary material has a lower burden than primary material. The results of this comparison are shown in Fig. 6.

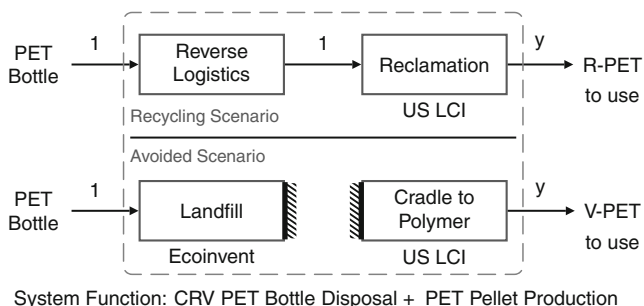


Fig. 2 Process diagram applying system expansion to the PET bottle system

3 Results

Figures 3 and 4 show our inventory and impact indicator results for the product system. For each category, the data axis (horizontal) is scaled to the total pre-consumer impact of the product system so that pre- and post-consumer phases can be compared. The post-consumer phase is shown in the three stages of hand-to-bale, bale-to-reclaimer, and reclamation. Bars for alternative pathways are stacked vertically, and each stage is aligned horizontally to the maximum-impact pathway of the prior stage.

3.1 Reverse logistics

The volume statistics provided by CalRecycle show that collection is distributed across the state and closely follows county populations. Of California's 58 counties, 56 reported collection of CRV PET bottles in each year from 2001 to 2009. The two counties reporting no collection, Sierra and Alpine, have a combined population of fewer than 4,500 individuals (California Department of Finance 2010). The remaining counties report about 4–5 kg PET collected/capita/year with a highly linear correlation ($R^2 > 0.99$). Residential curbside collection programs accounted for 11 % of PET CRV deposit redemptions and 13.4 % of all PET recovery in 2009.

In contrast, processing is much more centralized and occurs primarily near urban centers. The number of counties with operating processors increased from 21 in 2001 to 33 in 2009. However, surplus processing volume was limited to a small set of counties. Only Alameda, Fresno, Los Angeles, Sacramento, and San Bernardino counties had a processing surplus in every year for which data were available. Additionally, Riverside county (adjacent to both San Bernardino and Los Angeles counties) reported a surplus each year since 2005. These six counties accounted for 52–53 % of all PET collected and 75–79 % of all PET processed statewide for recent years. No other county reported a surplus of processing volume exceeding 2 % of collections. In total, about 25–35 % of PET was transported to another county for processing. We find the average distance traveled by a bottle from hand to bale is 145–175 km.

3.2 Inventory requirements

Figure 3 shows the energy, transportation, and waste disposal requirements of the product system during pre-consumer versus post-consumer phases. Pre-consumer processes were the dominant source of primary energy demand, requiring 3.95 MJ ncv of primary energy to deliver 1 L of beverage. Of this amount, 1.32 MJ was the calorific value of fossil feedstocks used to make the PET. In the post-consumer phase, landfilling had the smallest requirements

1 L CRV Beverage (35.8 g PET; 5.0 g PP) – Inventory Requirements

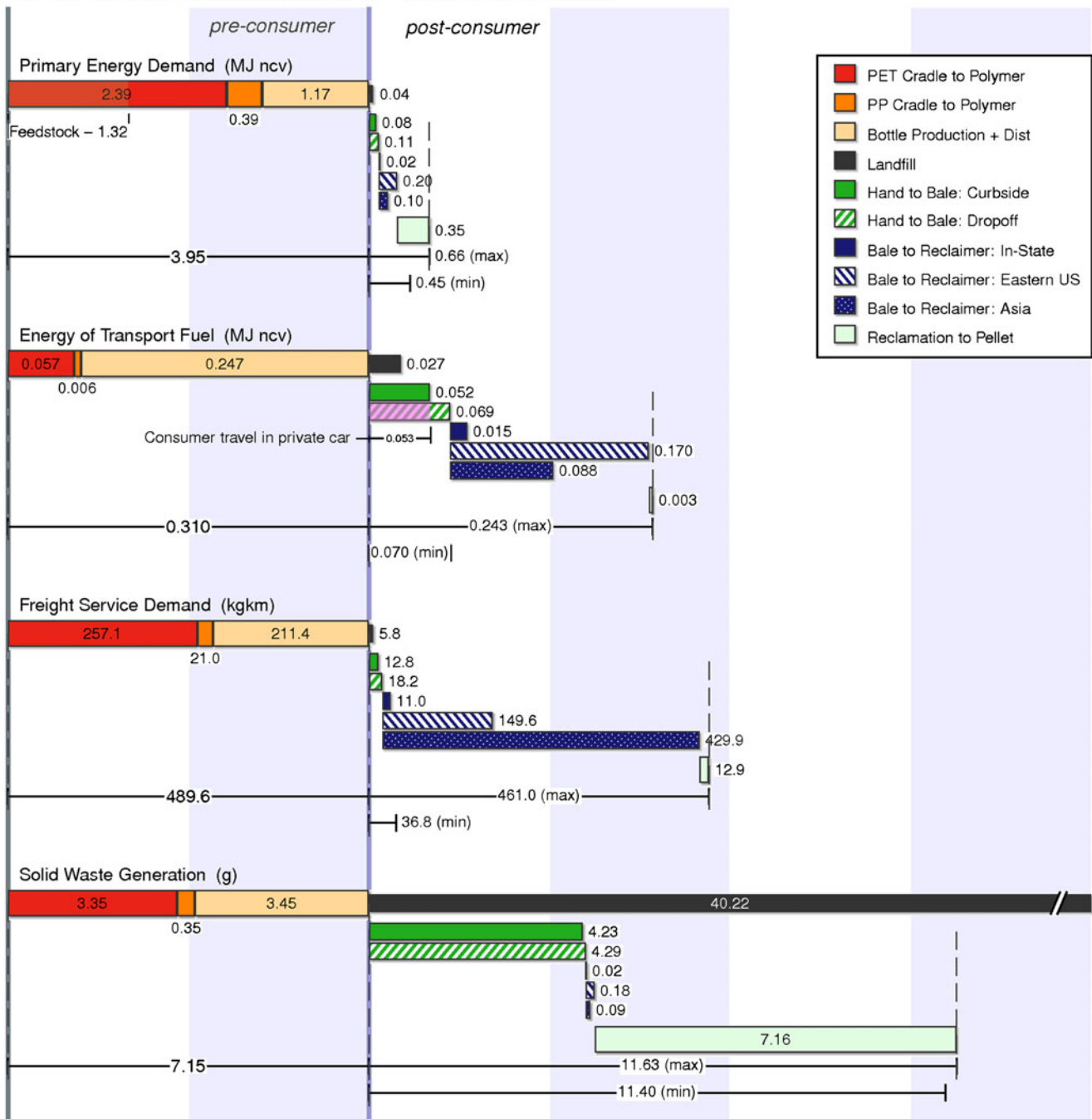


Fig. 3 Inventory indicators for the product system. Each category's horizontal axis is normalized to pre-consumer impacts

for energy and transportation but did not result in the generation of secondary material. Recycling of bottles (from discard through reclamation) required 0.45–0.66 MJ ncv. The drop-off pathway was more energy-intensive than the curbside pathway, though both comprised only a few percent of pre-consumer energy demand. The most expensive route in terms of energy demand was consumer drop-off followed by transport to an out-of-state reclaimer. The most

energy-efficient route is curbside collection followed by delivery to an in-state reclaimer.

Between 16 and 37 % of energy demand during the post-consumer phase is consumed directly by transportation processes. The remainder is used in sorting and reclamation facilities and consumed in the fuel cycle. The total energy of transport fuel required post-consumer is 0.07–0.24 MJ, with the majority of the high-end result dominated by truck

1 L CRV Beverage (35.8 g PET; 5.0 g PP) – Impacts

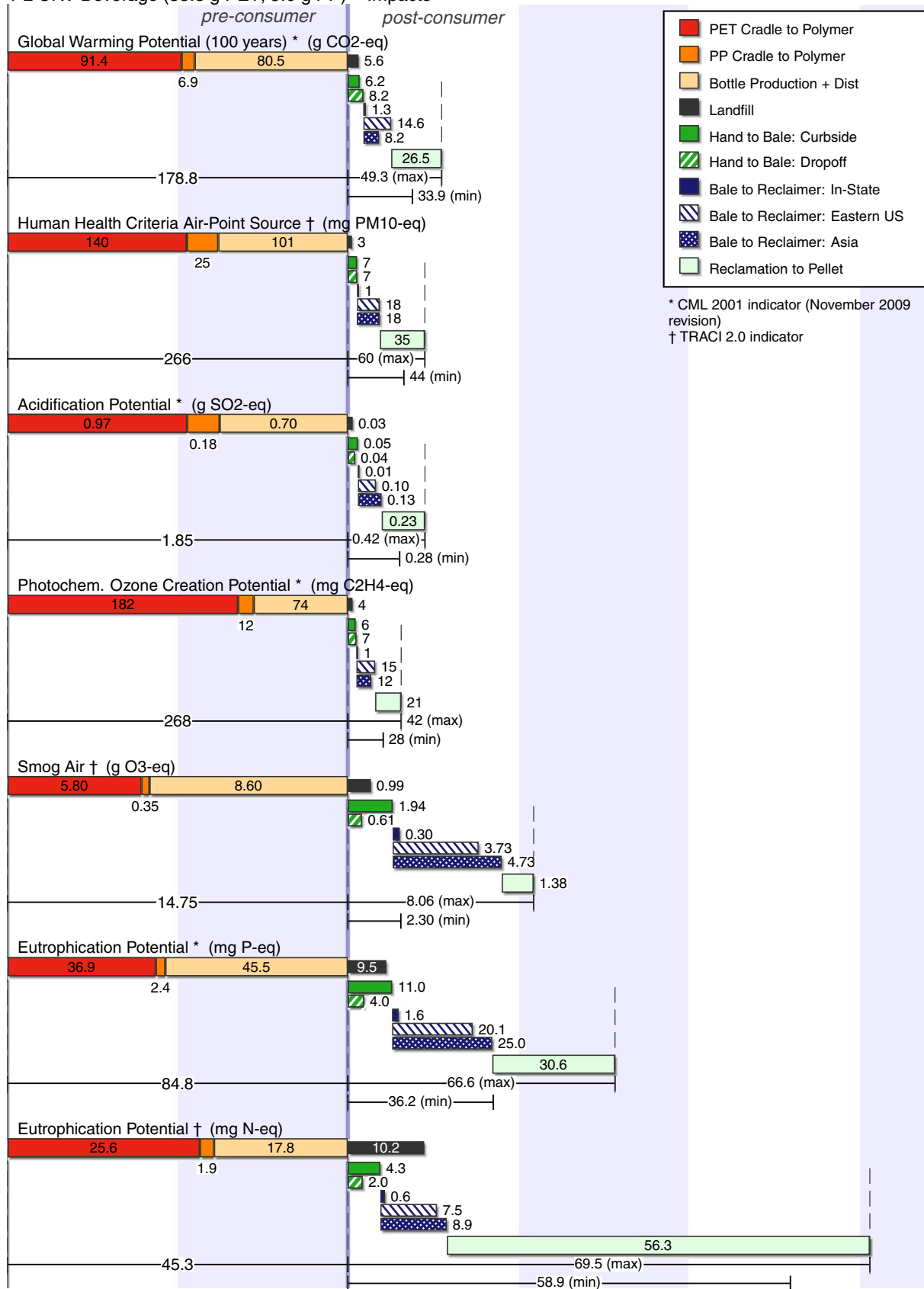


Fig. 4 Environmental impact indicators

transport to an out-of-state reclaimer. The amount of transport fuel associated with shipment to an out-of-state domestic reclaimer is comparable to the transportation energy required during bottle manufacture. In the bottle manufacture stage, the polymer is making the opposite journey, from an out-of-state polymer producer to an in-state bottling plant.

Freight service demand in the pre-consumer phase is about 490 kgkm/L of beverage delivered, balanced between inbound logistics to the polymer and manufacturing phases. Much of the pre-polymer transportation is accomplished via pipeline or ocean freight, leading to its relatively low requirements for transport energy. Post-consumer freight requirements range from 40 to 460 kgkm, the high end being dominated by 430 kgkm ocean freight to Asia.

Waste disposal requirements were dominated by the post-consumer phase. The landfill pathway produced the greatest requirement, resulting from the disposal of the entire PET bottle plus cap and label. In other pathways, landfill waste is generated from PP caps discarded during the hand-to-bale stage, as well as yield losses during reclamation. In all, delivery of the functional unit generates 47 g of solid waste when bottles are disposed in landfill, versus 18–19 g of solid waste when bottles are recycled.

3.3 Environmental impacts

Figure 4 shows the results of several environmental impact indicators, comparing pre-consumer to post-consumer impacts. Landfilling was found to have the smallest impacts in every category, although this form of disposal results in loss of the material. In the TRACI-2.0 eutrophication category, post-consumer impacts exceeded pre-consumer impacts regardless of the pathway taken by the discarded bottles. In all other indicators, post-consumer impacts were lower in magnitude than pre-consumer impacts, often significantly lower. The global warming potential of the post-consumer phase was 34–49 g CO₂-eq/L of beverage packaging recycled, versus 179 g/L beverage for the pre-consumer phase. Acidification potential, photochemical ozone creation potential, and criteria pollutants were comparable, showing that post-consumer activity contributed between 10 and 25 % of pre-consumer impacts, depending on pathway. Smog (TRACI-2.0) and photochemical oxidation creation (CML) showed very different results despite being indicators for roughly the same category. The difference appears to be attributable mainly to different characterizations of NO_x emissions in the two indicators.

In all categories except for smog, reclamation to R-PET pellet was the dominant source of post-consumer impacts, followed by bale-to-reclaimer logistics for long-distance shipping to the Eastern US or to Asia. In the smog category, reverse logistics were dominant. Reclamation carried

significant eutrophication impacts because of its generation of waste water for cleaning PET flakes. Impacts from wastewater emissions arising from the reclamation process accounted for 57 % (CML) or 70 % (TRACI-2.0) of the eutrophication impacts from the reclamation stage. According to the TRACI indicator, these direct process emissions accounted for more impacts than any other life cycle stage. However, process emissions were much less significant in the CML eutrophication indicator. Other indicator scores from reclamation can be traced to energy production and sodium hydroxide production.

Impacts from the hand-to-bale stage amounted to less than 5 % of the impacts from pre-consumer activity in most cases. The exceptions come from curbside vehicle operation, which contributes notably to smog and eutrophication impacts. In both categories, NO_x emissions are dominant. These high-impact scores originate in part from modeling waste collection vehicle operation as heavy equipment, a high-emission assumption that is nonetheless in line with some published empirical results (Chilton et al. 2010). Our waste collection data set includes emissions of NO_x that are 57 % higher/L of fuel than the data set for freight transport, accounting for a portion of the high scores.

3.4 Hand-to-bale sensitivity analysis

The hand-to-bale stage made up a small share of all impact categories. In almost all indicators, the impact from this stage was less than 5 % of the pre-consumer phase. The exceptions were smog and eutrophication from curbside collection. Impacts from landfilling were comparable in magnitude to impacts from the hand-to-bale stage. We tested the sensitivity of the indicators from this stage to changes in model parameters. For the curbside pathway, we evaluated the following parameters (baseline values correspond to the results reported in Figs. 2, 3, and 4):

- Curbside fuel: (13–30 L/t) fuel usage/tonne of commingled recycling (baseline, 20 L/t);
- Long-haul fraction: (0–100 %) portion of curbside collection that is processed in another county (baseline: 20 %);
- MRF Electricity use, 24–140 MJ/t (baseline: 58 MJ/t).

For the drop-off pathway, we evaluated:

- Private vehicle allocation: (0–100 %) Share of a 1.6-km round trip allocated to 1 kg PET bottles (baseline, 25 %);
- Long-haul fraction: (0–100 %) portion of drop-off recycling that is processed in another county (baseline, 35 %).

The results are shown in Fig. 5, reported as a fraction of pre-consumer impacts for each category, and compared with the impacts incurred from disposal in a landfill. Curbside

fuel use and private vehicle allocation were found to contribute most significantly to the impacts of their respective pathways. In contrast, MRF electricity use appeared to make a negligible contribution.

The allocation of a consumer's trip to a drop-off facility was the parameter which had the greatest proportionate effect on total impacts of the hand-to-bale stage. Under the baseline scenario (one-quarter of a consumer's trip allocated to PET bottles), energy demand due to personal transportation amounted to 58 % of primary energy demand for the hand-to-bale stage. Under a 100 % allocation, energy demand and global warming potential are nearly tripled. There is a wide range of reasonable allocations for this data point; however, the statewide average is likely to be low for a number of reasons. First, because many recycling centers are located in immediate proximity to supermarkets, the distance traveled is often likely to be shorter than 1.6 km (CalRecycle 2011a, b). Second, many bottles are likely to be redeemed in large quantities by individuals who obtain a considerable income through recycling (Ashenmiller 2009).

Both of these factors point to a relatively lower effective allocation for many bottles. On the other hand, consumers who allow their vehicles to idle for long periods during CRV redemption or otherwise behave irresponsibly with respect to energy usage may impart dramatically higher emissions than are accounted in the model. These emissions can reasonably be excluded from the system boundary.

Fuel usage during curbside collection represents the most significant parameter in the curbside route. This data point was found to be widely varied across the curbside programs that provided data, and depends on population density, area covered, number of subscribers, and equipment model and age. Curbside programs were found throughout the full range of fuel consumption estimates. The baseline value we selected was a volume-weighted average of available data and is comparable to values published in the literature (Beigl and Salhofer 2004; Chester et al. 2008; Chilton et al. 2010; US LCI 2011). It is likely that several programs, particularly in areas of high population density, will be towards the lower end of the range. Fuel usage and

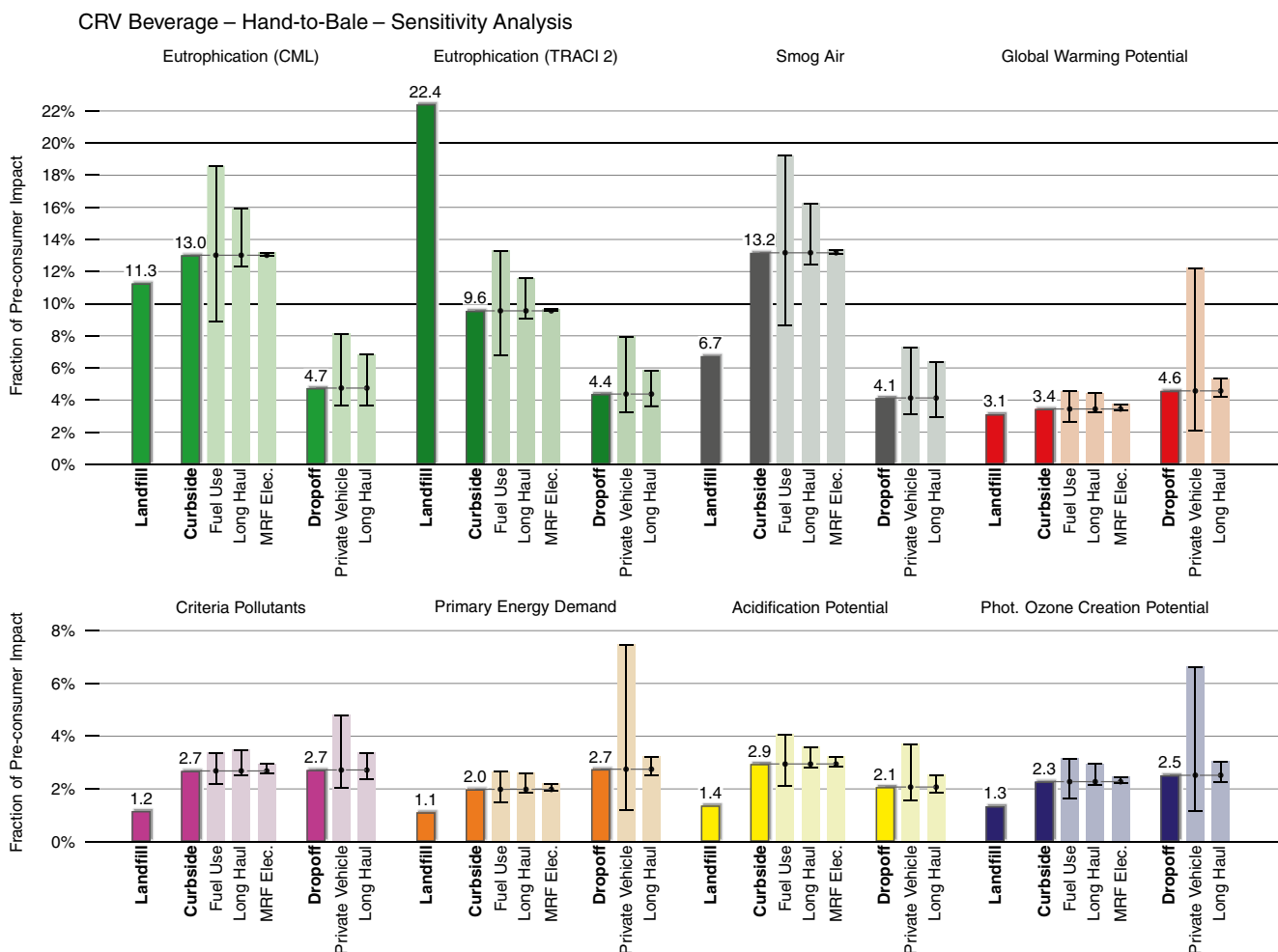


Fig. 5 Hand-to-bale stage: sensitivity to inventory parameters

environmental impacts from curbside collection can also be reduced through improved equipment efficiency and emission controls.

The long-haul fraction parameter measured the amount of material in each pathway that was shipped to another county for processing. Because the in-county and out-of-county distances were fixed, this parameter effectively modeled the distance each bottle was shipped. We found that this parameter had a significant but minor effect on total impacts. Moreover, the baseline values are likely to be close to the actual values based on per-county collection and processing volumes (see Section 2.4.3). We observe that a long-haul fraction of 100 % would represent an exceedingly inefficient allocation of freight resources, which is unlikely considering the large number and geographic range of operating processors in the state. In particular, it is judged highly unlikely that a large share of curbside commingled recycling is shipped as far as 350 km for processing, although it may occur in rural areas.

3.5 Relative burdens of secondary production

We compared the environmental impact of bottle recycling to the impact of producing an equivalent amount of primary PET using system expansion, as shown in Fig. 2. Figure 6 reports our results as a ratio of burdens from recycling over burdens avoided through recycling (Eq. 1). Colored bars and numerical scores correspond to the baseline results as shown in Figs. 3, and 4 for each combination of logistical pathways. The error bars represent the total variation across all sensitivity parameters in that category for that route, as shown previously in Fig. 5. In this figure, a score greater than one indicates that recycling has a greater burden than the avoided processes in that impact indicator for a particular end-of-life pathway.

The results show that recycling leads to a clear reduction in global warming, criteria pollutants, primary energy demand, acidification, and photochemical ozone creation (CML). Smog (TRACI-2.0) and eutrophication (CML) indicator results are marginal and the sign of the net burden depends on the choice of logistical pathway. Eutrophication impacts according to the TRACI 2.0 indicator showed a particularly marked increase under recycling due to wastewater emissions from the reclamation process. In this indicator, recycling carries a greater burden than primary production for all logistical pathways.

In all cases, in-state reclamation had the lowest impacts of any bale-to-reclaimer pathway, although in most categories there appeared to be a relative reduction in burdens regardless of route. Bale-to-reclaimer logistics are decisive in the smog (TRACI-2.0) indicator, with in-state reclamation leading to a relative reduction in environmental burdens

and out-of-state reclamation pathways leading to greater smog emissions. In other categories, in-state reclamation had a smaller effect but was still beneficial.

4 Discussion

We modeled the environmental impacts of PET bottle recycling under California's CRV deposit program during 2007–2009. Our results have three significant implications. First, the activities within the scope of the CRV program, identified in this paper as the hand-to-bale stage, have small impacts in comparison to the life cycle of the product. Overall impacts from this stage amount to 2–15 % of pre-consumer impacts. Our sensitivity analysis shows that our results are robust to significant parameter variation. This finding supports the premise that the collection of post-consumer disposable packaging does not in itself carry significant environmental impacts relative to the life cycle of the packaging. The categories in which hand-to-bale impacts were greatest relative to pre-consumer impacts, namely smog and eutrophication from curbside collection, include pessimistic assumptions about the level of NO_x emissions resulting from waste vehicle operation. The operation of modern vehicles with functioning emission control systems may significantly lower NO_x emissions during the collection stage.

Second, the most environmentally significant end-of-life decision is the choice of reclaimer for post-consumer bottles. Transport of bottles to an in-state reclaimer has modestly lower impacts in all categories, and is dramatically lower in the smog category. The selection of an out-of-state reclaimer can shift recycling from favorable to unfavorable with respect to smog impacts. Moreover, the location at which bottles are reclaimed also affects logistics for subsequent manufacturing stages. Because no primary PET is produced within California, there are significant transportation requirements associated with shipment of primary polymers to the state (Madival et al. 2009). If bottles were reclaimed, and the resulting R-PET used, within the state of California, then there may be further net savings due to avoided transportation in the pre-consumer phase.

Finally, our comparison of recycling impacts to avoided impacts shows that PET bottle recycling can lead to significant reductions in environmental impact in several impact categories, including categories of interest to California policymakers, such as global warming potential, provided that the recycled material displaces primary material. Eutrophication (TRACI-2.0) is the only impact indicator for which post-consumer impacts exceed those of the pre-consumer phase regardless of end-of-life route. This is due to wastewater emissions from reclamation activities, and so this result is likely to be very sensitive to

CRV PET Bottle – Burdens from Recycling vs. Avoided Burden

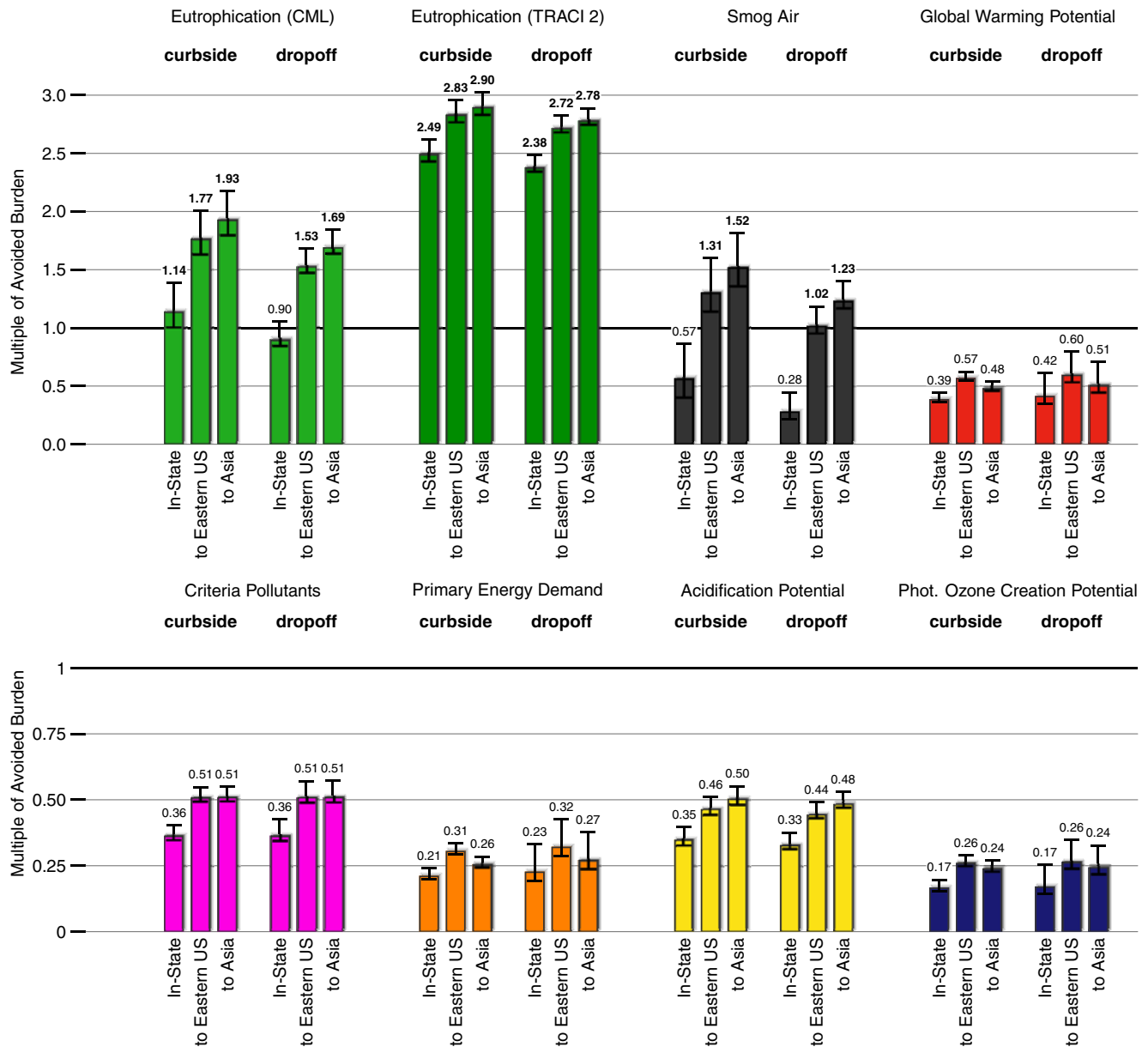


Fig. 6 Environmental burdens of secondary production from recycled bottles compared to burdens from avoided processes

wastewater treatment techniques. The CML eutrophication indicator showed smaller burdens from secondary production, and for drop-off recycling followed by in-state reclamation, this indicator shows a net reduction in burdens.

It is important to note that, due to a lack of US data, our model compares Ecoinvent disposal processes describing Swiss conditions to US LCI fuel cycle processes, so discrepancies in modeling between the two data sources may lead to a faulty comparison in areas where waste disposal impacts are significant. There appears to be no authoritative process inventory for solid waste disposal under US

conditions, a data gap that should be investigated by the LCA community.

Our sensitivity analysis shows that allocation of collection impacts to PET bottles is an important consideration. In particular, curbside collection programs that are very fuel-intensive and/or transport their wastes to a remote county for processing have higher impacts than consumer drop-off programs. On the other hand, consumers who make energy-intensive long trips to deliver relatively small quantities of bottles to recycling centers can lead to much higher energy consumption and greenhouse-gas emissions than alternative collection methods. The PET allocation in the

consumer vehicle transport process was the most influential modeling decision in the hand-to-bale stage.

Our results suggest that deposit programs on disposable packaging are a useful policy mechanism to improve environmental performance because they have the potential to generate a large stream of post-consumer material with low environmental impacts. In California and other states with deposit programs, the recovery rate for beverage containers far exceeds the rate found in non-deposit states (Container Recycling Institute 2008). Deposit programs applied to other disposable packaging product systems should be considered. Rigid thermoformed containers made of PET or R-PET are ideal candidates because they are increasingly abundant and can potentially be incorporated into the existing PET recycling infrastructure (National Association for PET Container Resources 2010). Building on the mature post-consumer PET market, the expansion of deposit programs and other incentives could bring about the recycling of a broad array of PET and R-PET single-use packaging geographically close to the point of consumption. The savings on energy resources as well as forward and reverse logistics arising from this style of materials management could be immense and should be the subject of future study.

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