Resources, Conservation and Recycling 61 (2012) 1–15

Contents lists available at SciVerse ScienceDirect

Resources, Conservation and Recycling

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

Water accounting for (agro)industrial operations and its application to energy pathways

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ARTICLE INFO

Article history:
Received 15 December 2011
Accepted 28 December 2011

Keywords:
Water accounting
Industrial operation
Energy pathways

ABSTRACT

Discussions about the water needed for the provision of goods and services have been hampered by a lack of a generic water-accounting methodology from the industrial operations perspective. We propose a methodology based on the concept of "economic water stress" that enables the assessment of water-related risks at the level of an industrial site and the level of an industrial supply chain or pathway. We then rigorously apply it to quantify the freshwater withdrawal and consumption needed for fuel and electricity supply chains. Those data make it possible to present, in comparable source-to-service terms, estimates of the freshwater intensities of mobility. Most of the estimated supply-chain and pathway freshwater intensities range over orders of magnitude on account of the variety of technologies and geographic locations. On average, fuels from unconventional fossil resources and biofuels derived from irrigated crops have higher freshwater withdrawal and consumption than conventional fossil fuels. Cooling in thermal power generation can also make severe demands on freshwater withdrawal and consumption, but technological options are available for most levels of freshwater scarcity. The mobility results reveal that vehicles with internal-combustion engines and electric motors have biofuel and power-generation technology options that lie roughly within the same freshwater-intensity ranges as that of conventional transport based on refined oil. In any case, the local context is critical: industrial sites with high freshwater withdrawal and consumption may be sustainable if there is ample water supply. Conversely, low freshwater withdrawal and consumption may be unsustainable in water-stressed regions.

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1. Introduction

Freshwater – or, to be more precise, liquid economically accessible freshwater – is already a scarce resource. A growing world population, rising per capita GDP and the changing global climate will only increase its scarcity under business-as-usual scenarios (Addams et al., 2009). Although the scarcity of freshwater is a global issue, its resourcing is always local. The consequences of its unavailability therefore tend to be most immediately felt by the users – both commercial and residential – of particular water basins.

Businesses throughout the world must therefore increasingly confront the localised risks of water stress. Physical disruptions of supply, changes to the regulatory regime and prohibitively high costs of supply are some of these risks (Environmental Resources Management Ltd., 2010). So too is the reputational damage from the perceived misuse of this precious resource. But such risks also have their business-opportunity upsides. By managing water-related risks and opportunities well, companies can build a competitive advantage and ensure that they have society's "licence" to operate.

A company should therefore be able to assess the cost and benefits of water-related options. But a generally accepted methodology for accounting operational water use does not exist (Morrison et al., 2010). Existing water-accounting methodologies, such as the Water Footprint and Life Cycle Assessments, approach the problem from a non-industrial[1] operations perspective. This is surprising in view of the fact that industries throughout the world extract more groundwater by mass than oil, gravel or other mineral and metal resources (Barth et al., 2010).

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[1] For the purposes of this paper, we regard any civil or commercial technology-based activity as an industry. Hence, both agriculture and the provision of water utilities are industries.

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doi:10.1016/j.resconrec.2011.12.011

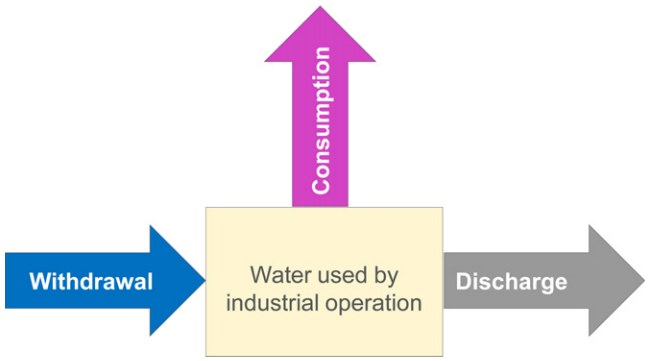


Fig. 1. Off-stream water use defined in terms of on-site water flows.

In this paper we propose a generic water-accounting methodology based on a set of requirements for industrial operations. Our methodology enables companies to assess managerial or technical options to deal with water stress not only for a given operational site but also for an entire industrial supply chain or energy pathway. The term “supply chain” is well-known: it includes all industrial operations from the development of raw-material sources to the delivery of a derived product, such as from crude oil to gasoline. An energy pathway is an extension of the supply chain, but rather than linking raw-material sources to an end product it links them to an end service, such as from crude oil to mobility. Industrial pathways thus encompass supply chains, but the reverse is not true.

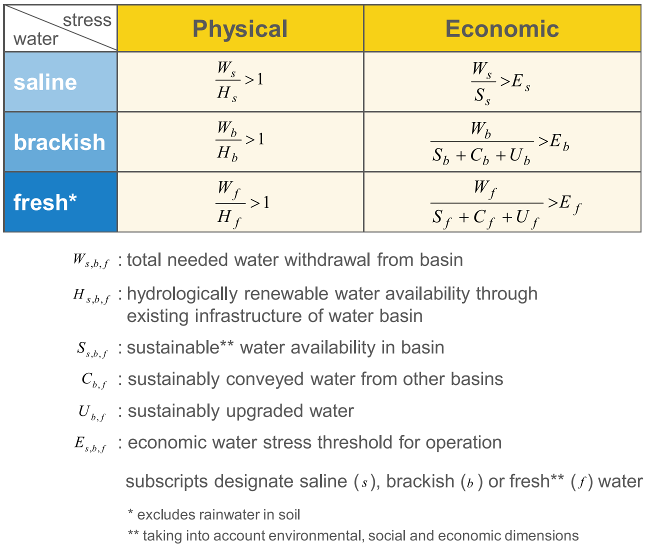
We show how three existing water-accounting methodologies do not meet the industrial requirements, because they were developed for other purposes. We then apply our methodology to compile and – when necessary – calculate a comprehensive set of freshwater-intensity values for the supply chains for fuels and electricity. To the best of our knowledge, this paper is the first to derive these estimates in a transparent fashion from the operational perspective. These values of freshwater consumption and withdrawal per unit of energy ultimately make it possible for us to frame a source-to-service pathway comparison of mobility.

2. Industrial water use

Virtually every industry uses water. In some cases, such as with hydropower or maritime shipping, it is used in-stream. In other cases, such as in manufacturing, water is used off-stream: it is removed from a natural body of water. An industrial operation that uses water off-stream *withdraws* water from the local water system, *consumes* part of this and *discharges* the rest after use (see Fig. 1 and Table 1).

Table 1
Definitions of water flows crossing the boundaries of industrial sites.

Terms	Definition
Withdrawal	Inflow of water from surface water, groundwater, collected rainwater, the municipal water supply or the sea for any use (based on Global Reporting Initiative (2010)).
Consumption	Outflow of water by evaporation, transpiration, product embedment and chemical conversion as well as through discharge into non-adjacent water basins (based on Bayart et al. (2010)).
Discharge	The sum of water effluents from an industrial operation that flow into the original or an adjacent water basin. The effluents can include water that is a by-product of the operation itself, say, from a chemical reaction or the processing of succulent biomass. Receiving bodies include surface and subsurface waters and sewers that eventually lead to rivers, lakes, wetlands and oceans.



stress / water	Physical	Economic
saline	$\frac{W_s}{H_s} > 1$	$\frac{W_s}{S_s} > E_s$
brackish	$\frac{W_b}{H_b} > 1$	$\frac{W_b}{S_b + C_b + U_b} > E_b$
fresh*	$\frac{W_f}{H_f} > 1$	$\frac{W_f}{S_f + C_f + U_f} > E_f$

$W_{s,b,f}$: total needed water withdrawal from basin
$H_{s,b,f}$: hydrologically renewable water availability through existing infrastructure of water basin
$S_{s,b,f}$: sustainable** water availability in basin
$C_{b,f}$: sustainably conveyed water from other basins
$U_{b,f}$: sustainably upgraded water
$E_{s,b,f}$: economic water stress threshold for operation

subscripts designate saline (s), brackish (b) or fresh** (f) water

* excludes rainwater in soil
** taking into account environmental, social and economic dimensions

Fig. 2. Physical and economic water stress defined for a given water basin.

2.1. Water stress

Various metrics of water stress have been defined (Fingerman et al., 2011; Berger and Finkbeiner, 2010). But economic water stress, as we define it in Fig. 2, is what affects industrial operations.

As depicted in Fig. 3, industrial water can be secured directly from the local basin, by importing it from another basin or by upgrading it through treatment. Economic water stress occurs when an industrial operation is effectively curtailed by the cost of securing water that meets the operation’s specifications within the environmental, social and economic restrictions of regulations. This differs from physical water stress, which arises when sufficient water of a given quality cannot be delivered through existing infrastructure. Within a given region, both physical and economic water stress can be induced, because water consumption and discharge of one industrial site reduces the water availability for other withdrawal sites in the same water basin.

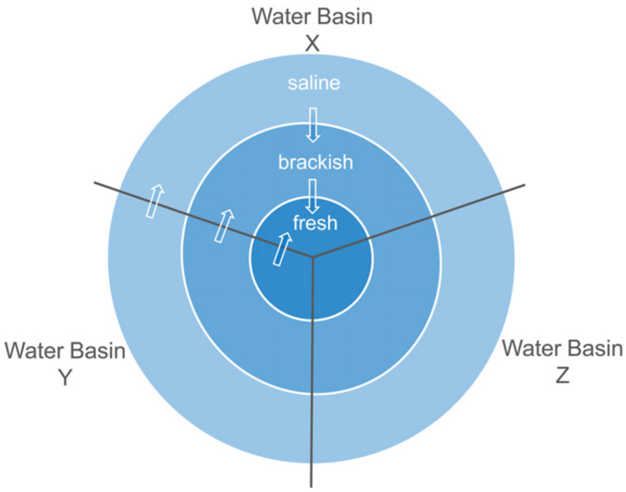


Fig. 3. Upgrading and inter-basin conveyance of water. Water is conveyed into Water Basin X, and it is also upgraded within the basin. Physical water stress can always be counteracted with technological and/or infrastructural measures as shown in water basin X; the question is whether these measures are economically and environmentally sustainable.

2.2. Resource and regulatory constraints

Economic water stress gives rise to water-scarcity constraints, two types of which can be discriminated. A *resource constraint* occurs when the industrial operation lacks economic access to sufficient water resources to continue its operations. A *regulatory constraint* occurs when the authorities of water-stressed regions ration water to ensure a sustainable allocation. The right to potable water, for example, is explicitly listed in various international human-right treaties and principles (Office of the United Nations High Commissioner for Human Rights, 2011).

Different regulatory constraints may be imposed on withdrawal, consumption and discharge. For that reason it is important to account for each separately. As depicted in Fig. 4, water withdrawals that are returned to the original water basin do not reduce water availability for other users if the water is of similar – or improved – quality. Water consumption, in contrast, actually reduces water availability for other users. The water quality of discharges may also affect the availability of water of certain quality.

In sum, water resource and regulatory constraints can disrupt industrial operations to such an extent that "business as usual" becomes impossible. Water prices may become prohibitive, water may become unavailable for withdrawal or consumption, and the treatment and disposal of wastewater may become too costly.

2.3. Industrial response

Companies are becoming increasingly aware of the possibility of economic water stress and water constraints (Morrison and Schulte, 2009). As depicted in Fig. 4, companies that have their industrial operations located in water-stressed areas can investigate options to reduce their operations' vulnerability to disruption. Options include setting up new supply chains, implementing new technologies or formulating new business strategies. They, in turn, depend on corporate activities such as (based on Morrison et al. (2010)):

- water-related risk identification and assessment (e.g., to mitigate the risks with the highest exposure);
- assessment of the impact of water use on society and ecosystems (e.g., for regulatory compliance);
- enhancement of water efficiency through improved process design (e.g., to reduce operating costs);
- water-related strategic business planning (e.g., to set long-term goals); and
- disclosures about water usage and water-related risks to stakeholders – including the company's shareholders (e.g., to obtain a social "licence to operate" and to facilitate engagement with stakeholders).

2.4. Requirements of an industrial water-accounting methodology

The above-mentioned activities require a method for accounting water withdrawal, consumption and discharge from the operational perspective. Such accounting is complex because water is a "multifaceted good" (Addams et al., 2009). It can be differentiated by volume, source, purpose, quality, timing, location and reliability of supply. But the immediacy of freshwater stress makes it particularly tricky to handle in a systematic way. Water-scarcity constraints tend to be location specific. Therefore, water accounting from the industrial perspective should be site based and not product based. The manifestations of climate change, in contrast, are not directly coupled to the locations of CO_2 emissions. As a result, carbon accounting is both – site based within the context of, for example, cap-and-trade schemes and product based within the context of low-carbon fuel standards.

A practical methodology of industrial water accounting also needs to accommodate two distinct levels of aggregation: one at the level of the industrial site and the other at the level of an industrial pathway. The industrial-site level comprises all specific water flows across the boundaries of the site. The pathway level focuses on the total water demands from a typical source to the ultimate provision of a typical service to an end user. The pathway level for, say, lorry transportation fuelled by oil-based diesel aggregates all water withdrawal, consumption and discharge of the industrial activities involved in oil extraction, oil transport, oil refining, fuel distribution and driving a truck with an internal combustion engine.

The links in the supply chains of these higher-level, aggregated industrial pathways provide the nexus by which other resources can be brought into a multidimensional "stress equation". Water is increasingly being accounted for in the extraction and conversion of resources and agriculture. A *generic* water-accounting methodology – one that is applicable to all possible industrial pathways – would enable consistent comparisons of withdrawal, consumption and discharge intensities. The importance of an all-purpose industrial water-accounting methodology is further explained in this paper's supplementary document, which can be accessed via the Internet address given at the end of this paper.

2.4.1. Industrial sites

The purpose of water accounting at the industrial-site level is to facilitate the assessment of managerial, strategic and technological adaptations that reduces a site's exposure to water-related risks or that give it a competitive advantage.

- *Withdrawal:* Resource and regulatory constraints on the water withdrawals of industrial sites are specified in terms of volume, quality, source type, source location and time. Hence, assessing a site's response options to the imposition of water constraints requires an accounting methodology that specifies these parameters. Water quality is taken into account, because it determines both the water's availability and usage. The type of water source also is taken into account because the regulations for groundwater may differ from those for surface water – even if their qualities are the same. Lastly, water availabilities and regulations vary with location and time, so these parameters are specified as well. Indirect water withdrawal – that needed for the off-site production of energy and material inputs for the operation of an industrial site – is not accounted for, because it may occur at a location with different water-stress levels. In the end, it is the local water stress that constrains an industrial operation, not the water withdrawals of the entire supply chain to a product or pathway to a service.
- *Discharge:* Local regulatory constraints on direct water discharges are specified in terms of volume, quality, the receiving body, its location and time. Hence, a water-accounting methodology needs to incorporate these parameters in order to relate them to the local regulations. The nature of the receiving body, its location and the timing of the discharge are important as they influence the allowed quality and volume parameters. For example, regulations pertaining to thermal pollution are more stringent for discharge to rivers than to the sea – and they may also vary with season and climate.
- *Consumption:* If operations at the industrial site do not yield water as a by-product, then this flow can be determined from the difference between the volume of water withdrawn and the volume of water discharged. Because the quality of evaporated water is not specified, consumption cannot be used in combination with either withdrawal or discharge to determine the third water flow. For cases in which contaminated water may enter the

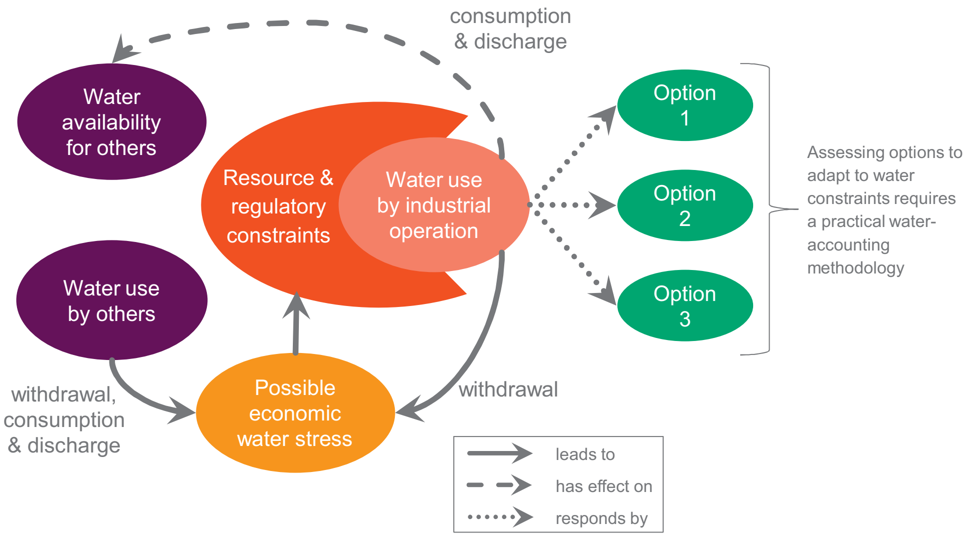


Fig. 4. Effects of resource and regulatory constraints on industrial operation in a given water basin.

environment through discharge to non-adjacent water basins (which is defined as consumption), a quality assessment is necessary to relate this water flow to regulatory compliance.

2.4.2. Industrial pathways

At the industrial-pathway level the freshwater use of every industrial site in a particular pathway is aggregated from the source to the service.

- *Withdrawal:* The aggregation of direct water withdrawals for each of a supply chain's links makes it impossible to differentiate between source type and source location at the industrial-pathway level. Source and location are both qualitative and unamenable to summing. Water quality cannot be easily characterised into a single numerical score, so water withdrawals at the industrial-pathway level are best expressed in terms of the measurable freshwater volumes withdrawn directly for a specific service. Methodologically it is possible, however, to quantify withdrawals of other water qualities.
- *Discharge:* Like the qualitative parameters of water withdrawals, those of water discharges cannot be usefully aggregated across multiple industrial sites. As a result, only one quantitative parameter – measurable volume of freshwater discharged – is considered.
- *Consumption:* Water consumption at the industrial-pathway level is also expressed purely in quantitative terms as the volume of freshwater consumed directly.

In contrast to the industrial-site level, any two of the three water flows are sufficient because water qualities of discharge and consumption are not specified; the third can subsequently be derived – provided that no water is chemically converted or no by-product water is discharged.

The industrial-pathway level is not appropriate for water-stress analysis, because the direct withdrawals that are summed up along the pathway to a service may come from different water basins. But such aggregation is useful for other purposes. It can facilitate the selection of adaptations that reduce water-related risks or that capitalise on water-related opportunities associated with the provision of a specific service, and it enables comparing freshwater intensities between activities within the same pathway or between different pathways that lead to the same service (e.g., ethanol production from maize vis-à-vis that from sugarcane).

Indirect freshwater withdrawals – say, for the generation of electricity – do pose a potential risk to a supply chain if they occur in water-stressed regions. However, the industrial operations associated with the indirect freshwater withdrawals must be evaluated separately (see Section 2.4.1).

An overview of the requirements for the parameter specifications of water flows at both the industrial-site and the industrial-pathway levels is given in the left-most column of Table 3.

3. Alternative water-accounting methodologies

Various methodologies to determine the water intensity of supplying products and services have been developed on the basis of different perspectives and objectives. Their differences have engendered much debate about the definition of water stress, the types of water use that should be accounted for, the handling of water-quality alterations and the level of aggregation – to name a few of the disputed topics.

Three of the most relevant available water-accounting methodologies are Life Cycle Assessment, the Water Footprint and the Global Water Tool. Depending on the perspective and objectives, different methodologies and scopes are needed (see Table 2). We briefly discuss them here to determine whether they meet the

Table 2
Overview of available water-accounting methodologies compared to the industrial operations perspective.

Methodology	Perspective	Objective
Life Cycle Assessment	Environmental impact assessment	Discourse on aggregated environmental impacts of products (Hoekstra et al., 2009).
Water Footprint	Water resource management	Discourse about sustainable, equitable and efficient freshwater use and allocation (Hoekstra et al., 2009).
Global Water Tool	Contextualisation of corporate water demands	Compilation of water-related data for assessment and communication of water-related risk.
Industrial water accounting	Industrial operations	Reduction of water-related risks and seizing water-related business opportunities for both industrial sites and industrial pathways.

Table 3
Water-accounting requirements for industrial applications and the evaluation of three relevant water-accounting methodologies.

	Industrial requirement	Life Cycle Assessment	Water Footprint	Global Water Tool
Operational-site level				
Withdrawal	1. Direct withdrawals differentiated by measurable volume, quality, source type, location and time period.	Proposed quality parameters are immeasurable or impractical; withdrawal is not included in stress evaluation.	Non-consumptive water withdrawal is excluded; accounts for freshwater only; includes indirect withdrawals.	Requirement met.
Discharge	2. Direct discharges differentiated by measurable volume, quality in relation to the local context, receiving body type, location and time period.	Proposed quality parameters are immeasurable or impractical; discharge water quality is not related to local regulations.	Discharge is not accounted for; "grey water" is not measurable.	Does not relate discharge water quality to local regulations.
Consumption	3. Direct consumption differentiated by measurable volume and quality in relation to the local context.	Proposed quality parameters are immeasurable or impractical.	Includes indirect freshwater consumption and "green water" (rainwater in soil); excludes discharge water to non-adjacent water basins.	Does not differentiate quality nor its relation to the local context.
Aggregated pathway level[a]				
Withdrawal	4. Direct freshwater withdrawals differentiated by volume required for a distinct pathway.	Theoretically possible but has not been explicitly delineated.	Non-consumptive water withdrawal is excluded; includes indirect withdrawals.	Does not aggregate withdrawal for a complete pathway.
Discharge	5. Direct discharges differentiated by volume required for a distinct pathway.	Theoretically possible but has not been explicitly delineated.	Discharge is not accounted for; "grey water" is not measurable.	Does not aggregate discharge for a complete pathway.
Consumption	6. Direct freshwater consumption differentiated by volume required for a distinct pathway.	Theoretically possible but has not been explicitly delineated.	Includes indirect freshwater consumption and "green water" (rainwater in soil), neither of which come from direct withdrawals.	Does not aggregate consumption for a complete pathway.

[a] Only two of the three pathway level requirements need to be satisfied when no by-product water is discharge.

industrial water-accounting requirements described earlier. Our conclusion is summarised in Table 3: without fundamental change, none of them would be capable of satisfying all the requirements for a practical, industry-based methodology. They may well be suitable for other purposes, but for assessing water-related *operational* risk and opportunities a new methodology is needed.

3.1. *Life Cycle Assessment*

A Life Cycle Assessment (LCA) evaluates the environmental impacts due to the existence of a given product or service. Despite the importance of freshwater for human health and environmental ecosystems, LCA methodologies have lacked a comprehensive scheme for characterising its use and the impact of its depletion (Owens, 2002; Koehler, 2008; Pfister et al., 2009; Milá i Canals et al., 2009; Bayart et al., 2010; Morrison et al., 2010; Berger and Finkbeiner, 2010). The Life Cycle Initiative launched a project in 2007 to redress this (Life Cycle Iniative, 2009).

In response, Bayart et al. (2010) have proposed a framework for inventorying and assessing off-stream freshwater use on the basis of the environmental impacts caused by the associated reductions in freshwater availability. Lower availabilities lead to more competition for access to freshwater and may eventually prevent access altogether. The resulting effects can then be analysed in terms of the newly proposed human-life, biotic-environment and abiotic-environment LCA impact categories as well as in terms of commonly accepted impact categories.

Bayart et al. (2010) gauge freshwater quality by means of either a distance-to-target or functionality approach. The distance-to-target approach measures the effort needed to process water so that it meets given target water-quality criteria. The effort can be quantified in terms of the energy required for purifying degraded water or in terms of the amount of "clean" water required to dilute degraded water until it meets the water-quality target. The functional approach, in contrast, assesses to which users the water withdrawn and discharged is functional. Water is functional when its quality parameters are within the accepted standards of the user.

Milá i Canals et al. (2009) have adopted an alternative LCA-based water accounting methodology. They base their life cycle inventory of freshwater use on four main "impact pathways", of which the first three are similar to those defined by Bayart et al. (2010): (1) changes in freshwater availability that affect human health; (2) changes in freshwater availability affecting ecosystem quality; (3) extraction of groundwater causing depletion; and (4) land use affecting the water cycle and hence ecosystem quality. They propose a pair of "evaporative use" impact indicators to quantify water stress due to Pathway 2 and the depletion potential due to Pathway 3.

Neither of these two proposed LCA inventory frameworks meet our industrial accounting requirements. Assessing inventory-water quality by means of Bayart et al.'s distance-to-target approach is not possible because it is physically unmeasureable if the water is not upgraded to the target quality, and the LCA functionality approach is foreign to most industries other than water utilities. Most industrial companies are concerned about water-quality specifications to the extent that they affect their own water use or to the extent that they meet regulations governing consumption and discharge.

Furthermore, the framework proposed by Milá i Canals et al. (2009) is based on a water-stress evaluation of water consumption (or "evaporative use"), not withdrawals. And LCAs, such as those applied to U.S. transportation fuels by Scown et al. (2011), often include indirect water withdrawals. From the industrial perspective, these should be evaluated separately.

3.2. *Water Footprint*

The Water Footprint is defined in terms of "blue", "grey" and "green" components, whose definitions are given in Table 4. These components can be considered separately or in aggregate, all being expressed in terms of water volumes.

The Water Footprint measures blue and green water consumption – not total withdrawals and discharges – and it uses the virtual grey Water Footprint as an indicator of water pollution. The quality of water is thus not explicitly defined.

The Water Footprint is inadequate for operational water accounting as it does not balance the water flows of an industrial operation. Moreover, indirect water consumption and green water are included. Indeed, green-water availability does play an

Table 4
Definitions of the three water-footprint components (Water Footprint Network, 2010).

Footprint component	Definition
Blue	Surface and groundwater consumed as a result of the production of a good or service.
Green	Rainwater consumed (from soil moisture) during the production process.
Grey	Water that would be required to dilute degraded water so that it just meets agreed water quality standards (i.e., so that the diluted water would contain the maximum acceptable concentration of pollutants).

important role in agriculture: the drier the region, the more difficult agriculture is. However, in our proposed freshwater stress evaluation, green-water availability is accounted for through blue-water demand for irrigation. If green water is lacking and blue water is hydrologically available, then blue-water withdrawals can sustain an agricultural operation – provided the economic means are available. Crops do not require an industrial operation to take in green water; in other words, crops do not "withdraw" green water. Irrigation of crops (blue water), on the other hand, does require industrial withdrawals from a water basin. From the regulatory perspective, accounting for green-water consumption also does not seem useful as soil moisture cannot be regulated. Rainwater usage, which may have detrimental effects on groundwater replenishment, can only be effectively regulated through restrictions on land use.

The Water Footprint Network claims its methodology addresses water use at different levels of aggregation for both consumers (a family, village, city, province or nation) and producers (a public organisation, private enterprise or economic sector). However, blue-water *withdrawals* and water *discharges* are not described in Water Footprint aggregations.

The Water Footprint does introduce national and international dimensions to the water resource debate, but it does not enable useful water-stress evaluations from an industrial perspective.

3.3. Global Water Tool

The Global Water Tool inventories a company's volumes of water withdrawn, consumed and discharged (WBCSD, 2010). The tool's water-discharge Excel worksheet makes provisions for the receiving body type and its location. The quality of both the withdrawals and discharges is distinguished by means of a dual category: freshwater or non-freshwater. The tool does not differentiate between upgraded, degraded or unchanged water. Nor does it relate discharged water to local regulations. The tool does aggregate water requirements, but companies will seldom operate along an entire pathway, from source to service.

The Global Water Tool provides a unique way to assess water-related risks for industrial sites in view of the water scarcities of the regions in which the sites are located. But it does not analyse water discharge in quality terms nor does it relate these to local regulations. It determines water use with the right level of specifications for aggregation (only volume), but it does not aggregate water use of pathways from source to service. Instead, the tool focuses on industrial operations in terms of site geography and water availability. Although the tool usefully contextualises company water demands on the basis of extensive compilations of various water-stress definitions and inventory data, it lacks a scientific methodology on which it can clearly stake out its territory in the water-accounting debate.

4. A generic industrial water-accounting methodology

In view of the lack of a practical, industry-based methodology, we propose one here. As depicted schematically in Fig. 5 for operational sites, it meets Requirements 1, 2 and 3: withdrawal parameters are measurable and differentiated by source, volume, quality, location and time; discharge parameters are measurable and differentiated by volume, quality, receiving body, location and time; and consumption parameters are measurable and differentiated by volume and quality in relation to the local context. As shown in Fig. 6, the methodology also makes it possible to aggregate water flows so as to meet Requirements 4, 5 and 6 at the pathway level.

4.1. Site-specific parameters

- *Withdrawal:* We specify six types of sources from which water can be withdrawn: oceans; surface water (including lakes, wetlands, rivers, and treated waste water off-site); groundwater; collected rainwater; municipal water; and off-site wastewater. Two major constituents of the earth's freshwater – glaciers and ice caps – have been excluded, since they are regarded as being unavailable for water withdrawals. The quality of water sources can be measured in terms of numerous chemical, physical and biological parameters. But the salinity of uncontaminated water is the most important factor in assessing whether the water can be used for industrial purposes – largely for land irrigation, or as a coolant or processing fluid. Water that is withdrawn from freshwater sources often requires less treatment to meet operational quality specifications, whereas brackish or saline water usually demands desalination. Still, some industrial operations do use saline or brackish water. Moreover, the risks and opportunities of using saline, brackish or freshwater for industrial purposes differ greatly. For accounting purposes, therefore, we distinguish the quality of the water withdrawn on the basis of whether it is fresh (<500 parts per million dissolved salts), brackish (500–30,000 ppm) or saline (>30,000 ppm).
- *Discharge:* Industrial operations can result in discharges of water having a lower quality grade than that of the withdrawal water. Authorities impose restrictions on the extent of this degradation by means of regulations. Some industrial operations, however, actually improve the quality of water or simply leave the water quality unchanged. The quality issues of discharge water are best regarded in terms of local environmental regulations. As shown in Fig. 5, a green flag indicates that the discharge flow from an industrial site meets the requirements of local regulations. A red flag, in contrast, indicates that the site's discharge flow does not meet local regulations; the site thus needs internal adaptations to comply. All water quality parameters need to be considered in determining the flag colour for a particular site. It is also important to account explicitly for the type of body that receives the discharged water and its location. Receiving bodies could be surface and subsurface waters as well as sewers that lead to wastewater treatment plants or to third parties, which then use the water. These can also be covered by local regulations.
- *Consumption:* The quantity of water consumed by evaporation and transpiration in industrial operations is generally not measured directly. Instead, it is usually determined from the difference between withdrawals and effluents – provided water is not a by-product of the industrial operation. Water that is embedded into products or chemically converted and effluents to non-adjacent basins also need to be regarded as consumption. Like discharges, consumption effluents must also be flagged according to their compliance with regulations.

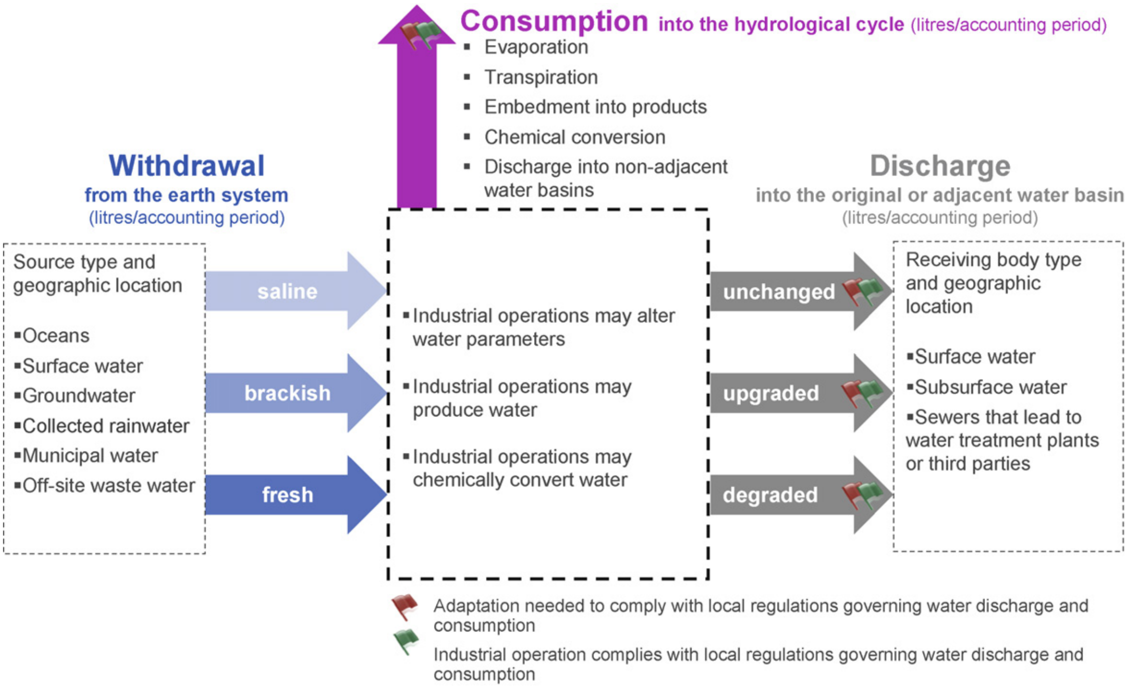


Fig. 5. Water-accounting methodology at the industrial-site level. Water parameters that may be altered by operations include: nutrient concentrations; biochemical oxygen demand; chemical concentrations; sediment; temperature; pH; and salinity. Operations may produce water, e.g., from a chemical reaction, the processing of water-rich biomass or the tapping of oil or gas fields.

4.2. Aggregation to industrial-pathway level

Unlike the water accounting at the industrial-site level, withdrawal and consumption at the industrial-pathway level are expressed only in terms of freshwater. Aggregating saline and brackish water withdrawals with those of freshwater would misrepresent a pathway's water intensities, because each water type carries different levels of risk. The types and locations of water sources tapped by the numerous links in a pathway cannot be summed, as these are not quantitative parameters. Similarly, the quality-specific parameters of discharge flows for the various pathway links cannot be aggregated as the regulations governing them vary with geographical location.

5. Source-to-carrier freshwater intensities

Ideally, the generic water-accounting methodology outlined in Section 4 should be implemented at the site level, where all the relevant data are collected to evaluate economic water stress and assess the site's options to adapt to water constraints. Once sufficient data have been amassed, then the site-level data can be aggregated to the supply chain or pathway level, where the water-related risks and

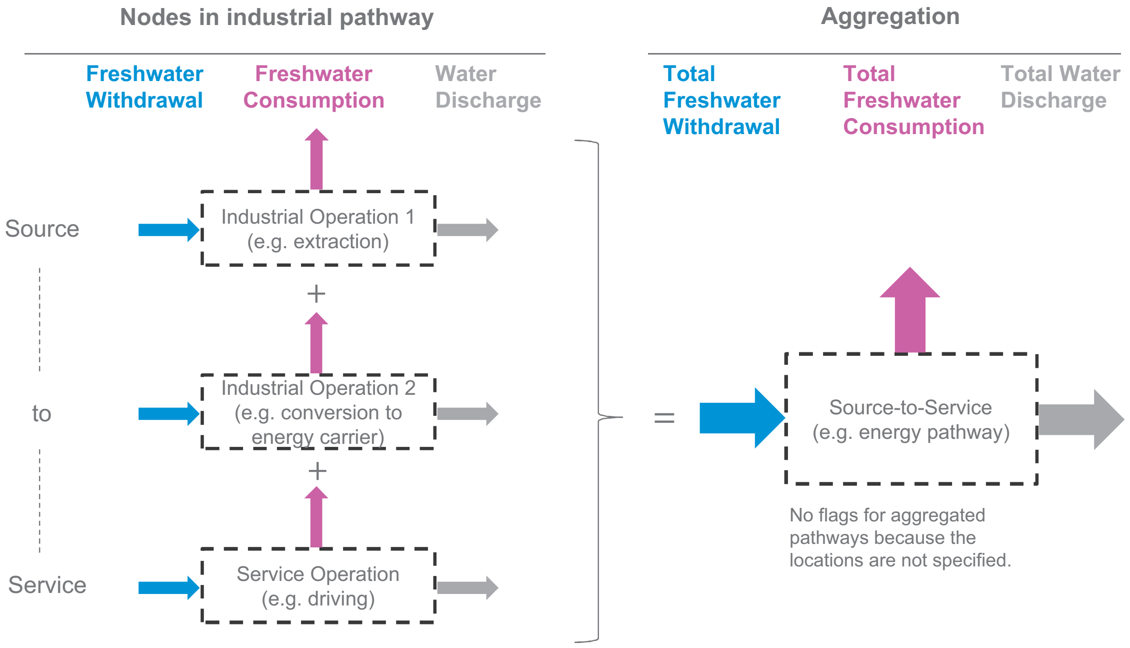


Fig. 6. Water-accounting methodology at the aggregated industrial-pathway level.

opportunities associated with the provision of a specific product or service can be compared.

However, no site-level data have yet been collected according to the principles of our water accounting methodology. To obtain our own estimates of the intensity of freshwater withdrawals and consumption associated with the source-to-carrier supply chains for fuels and electricity, we have relied on published estimates. But the lack of a generally accepted water-accounting methodology has precluded consistent reporting of water intensities. So we also investigated numerous peer-reviewed and non-peer-reviewed site-level reports to ascertain exactly what type of water was being accounted for in the published estimates. By presenting these data in such a methodologically rigorous manner from the industrial perspective, we hope that they help to identify those operations where future site-level analyses of an equally rigorous nature would be most revealing.

The industrial links in the various supply chains leading to the same energy carrier product may use different technologies and can be located in different water basins. Technologies influence water withdrawal and consumption requirements, the water bodies from which water can be withdrawn and the water bodies into which water can be discharged. The location of a particular industrial operation also imposes possible constraints on the bodies from which water can be withdrawn and into which it can be discharged by virtue of the local governing regulations. But location also influences technology. The physical availability of water of a certain quality in a certain region determines the water-related technology that ultimately prevails in the region.

To show this variety of interconnected technologies and locations, the water intensities for the aggregated industrial supply chains are depicted using ranges of values. Single-valued average freshwater intensities or midpoints of the freshwater intensity ranges are then determined to facilitate comparisons.

The details of the freshwater intensities' determination – including data uncertainties – are available in this paper's supplementary document. But a few words are in order here about the water consumption and withdrawal estimates of biofuel crops since their determination under our methodology differs markedly from that of the other fuels.

5.1. Approach to quantifying freshwater intensities of biofuel crops

Freshwater withdrawal and consumption for biomass production vary greatly with climate, soil water availability, soil structure, crop management, crop characteristics and irrigation technology (Wu et al., 2009; Perry et al., 2009). These factors are all location dependent. Hence, it is essential that freshwater withdrawal and consumption intensities for crop growth be determined not only by crop type but also by geographic region.

Geographically distinct and crop-specific freshwater withdrawal and consumption data are not readily available, however. An empirical approach to obtain the consumption data would be to divide annual irrigation withdrawals by the annual crop production and then multiply the quotient by the irrigation efficiency. The irrigation efficiency is the ratio of the volume of irrigation water made available for the evapotranspiration of a crop during its growth period to the volume of irrigation water withdrawn during the same period of time. This approach has limitations as regards the raw data availability:

- The necessary spatially explicit irrigation-withdrawal and crop-production data have not been compiled for all biofuel crops. Extensive research would thus be required to apply this empirical approach to all global biofuel crops and regions.
- Comparable data are also not available for food crops, making a direct comparison of energy and food crops difficult. Such comparisons can be important for policymaking.
- Irrigation-withdrawal data may be influenced by the particular weather, economics and crop-disease outbreaks in the year of collection.
- Irrigation efficiencies are not uniform over time or within a country.
- Non-productive freshwater consumption (water evaporated or transpired for purposes other than the intended use (Perry et al., 2009)) is excluded from the consumption data. These could be, for example, evaporation from water surfaces, unwanted riparian vegetation and wet soil.

An alternative is to use the CROPWAT model of the Food and Agriculture Organisation (FAO CROPWAT, 2011). It simulates the evapotranspiration of crops in different regions on the basis of parameters such as climate as well as soil water availability and quality. Absorbed rainwater (i.e., green water) needs to be deducted to ensure that only irrigation water (i.e., blue water) is accounted for in the freshwater consumption data thus generated. Dividing the freshwater consumption data by the irrigation efficiency of the region in which the crop is grown then yields an estimate of the freshwater withdrawal. Mekonnen and Hoekstra (2010) have published spatially explicit blue, grey and green water footprints for 126 crops for the period 1996–2005 using the CROPWAT model.

For our purposes, this approach has the following limitations:

- It is not based on actual measurements, giving rise to greater uncertainty.
- Irrigation efficiencies are not uniform over time or within a country.
- Non-productive freshwater consumption is excluded.

Despite its limitations, we used the CROPWAT approach together with irrigation efficiencies from Rohwer et al. (2007) to estimate spatially explicit and crop-specific freshwater consumptions and withdrawals for biomass production throughout the world. This enabled us to make a like-for-like comparison of biofuels with different origins. This contrasts with the reports of Mielke et al. (2010) and Glassman et al. (2011), which are limited to U.S. crops and do not include withdrawals for biomass production.

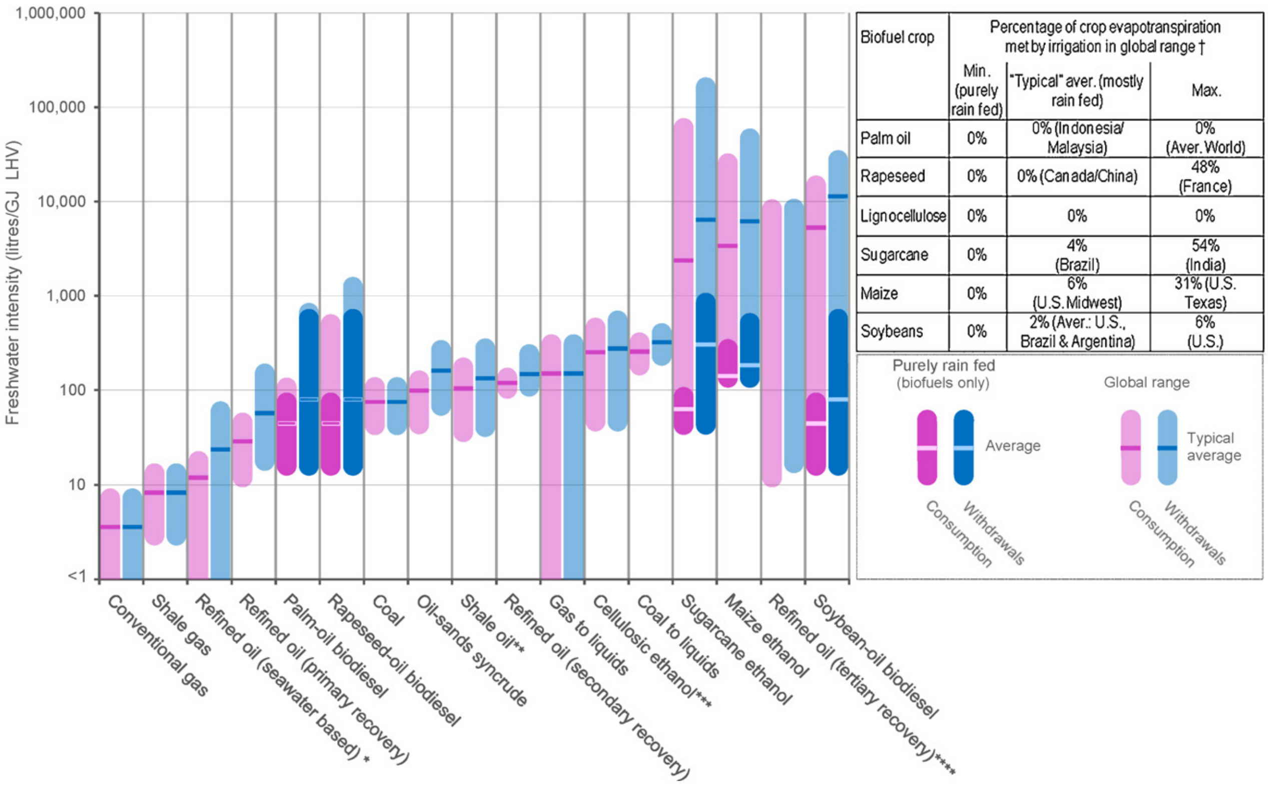
In determining the freshwater consumption and withdrawal ranges for specific biofuel crops, we focused on those countries where the crops in question are grown at large scales. The average freshwater consumption and withdrawal for the growing of a specific crop in its major production country (e.g., Brazil for sugarcane, the U.S. Midwest for maize, and Malaysia and Indonesia for palm fruit) is used to represent the crop-specific "typical average" freshwater consumption and withdrawal. The minima in the ranges are equated to zero: the crops are then "purely rain fed" and the biomass-to-fuel conversion process is entirely responsible for the freshwater intensities in the supply chain. The maxima in the ranges are selected using the highest average freshwater consumption level among those countries where the crop production is significant.

5.2. Results for fuels

Fig. 7 shows the freshwater consumption and withdrawal intensity ranges that we found or determined for various supply-chains leading to an energy-carrying fuel.

5.2.1. Gas

The freshwater withdrawal and consumption intensities for shale–gas production are approximately twice those of



Biofuel crop	Percentage of crop evapotranspiration met by irrigation in global range †		
	Min. (purely rain fed)	"Typical" aver. (mostly rain fed)	Max.
Palm oil	0%	0% (Indonesia/ Malaysia)	0% (Aver. World)
Rapeseed	0%	0% (Canada/China)	48% (France)
Lignocellulose	0%	0%	0%
Sugarcane	0%	4% (Brazil)	54% (India)
Maize	0%	6% (U.S. Midwest)	31% (U.S. Texas)
Soybeans	0%	2% (Aver.: U.S., Brazil & Argentina)	6% (U.S.)

Fig. 7. Source-to-carrier freshwater intensities for fuels production. LHV stands for lower heating value. *Based on seawater-injection oil recovery and refinery once-through seawater cooling. **Excludes upgrading to synthetic crude oil. ***Excludes water consumption for crop residues which are often allocated to food production. ****Range spans various technologies as shown in Fig. 8; no single average calculated. †The typical averages of the global ranges for biofuels are based on the national or regional average freshwater intensities for the growing of the crop in its major production country or region – except for the case of soybeans which is based on the average of the major production countries because no single country dominates worldwide production. The minimum consumption levels in the global ranges are based on zero freshwater intensities for biomass production: the crops are then exclusively rain fed. The purely rain-fed ranges – which lie within the global ranges – exclude irrigation and are thus equal to the freshwater intensities of the biomass-to-biofuel conversion plants. The maximum consumption levels are based on the highest average freshwater consumption level among those countries or regions where the crop production is significant.

conventional gas production. But both types of natural gas supply chains are less water intensive than other fossil-fuel energy supply chains. The freshwater intensity of shale–gas production largely depends on the amount of natural gas that is ultimately recovered per well, besides factors such as geology, drilling technology, freshwater availability and recycling, and regulations (Mielke et al., 2010). Water consumed by shale–gas operations may end up in water-bearing rock layers, so such operations should comply with regulations aimed at preventing groundwater contamination. As discussed in Section 1, site-level water accounting is not only about balancing water flows but also about checking regulatory compliance.

5.2.2. Coal

Freshwater intensities of coal supply chains are higher than those of gas but lower than those of most fuels. There are environmental concerns regarding water contamination from mining operations (Gleick, 1994). According to our methodology, site-level water accounts may show red compliance flags, depending on the extraction technology, the mine's location and the applicable regulations.

5.2.3. Oil

The freshwater intensity of fuels derived from crude oil depends on the techniques by which the oil is recovered – primary (using the field's natural pressure to drive the oil to the surface), secondary (injecting water into the field to sweep the oil to producing wells) or tertiary (injecting other substances into the field to loosen the oil or alter its flow properties). The source-to-carrier freshwater intensities of crude oil recovery and processing recovered by secondary means is significantly higher on average than those of primary recovered oil. But when saline or brackish water is used as the injection water and the refinery uses once-through seawater cooling and desalinated seawater as process water, then the oil-to-fuel pathway effectively has a negligible freshwater intensity.

Refined shale oil and bitumen have higher freshwater intensities than refined primary-recovered oil. The reason is the procurement of the feedstock. The average freshwater intensity of the production of shale oil, bitumen and secondary-recovery oil is between 4.5 and 8 times higher than that of crude oil recovered by primary means.

The freshwater intensities of tertiary oil recovery vary widely according to the technologies employed. Their averages are separately shown in Fig. 8.

5.2.4. Biofuels

"Typical average" freshwater intensities of biodiesel production from rapeseed and palm oil are on the same order of magnitude as those of refined oil with primary recovery. Average freshwater intensities of ethanol production from "purely rain-fed" maize (corresponding with biomass conversion freshwater intensities) are on the same order of magnitude as refined oil using secondary recovery. Biofuels production from "purely rain-fed" sugarcane falls in between those of refined oil using primary and secondary recovery. The average freshwater intensity of the lignocellulose-to-ethanol supply chain ranges between 1.7 and 8.8 times that of oil-to-gasoline supply chains based on either primary or secondary

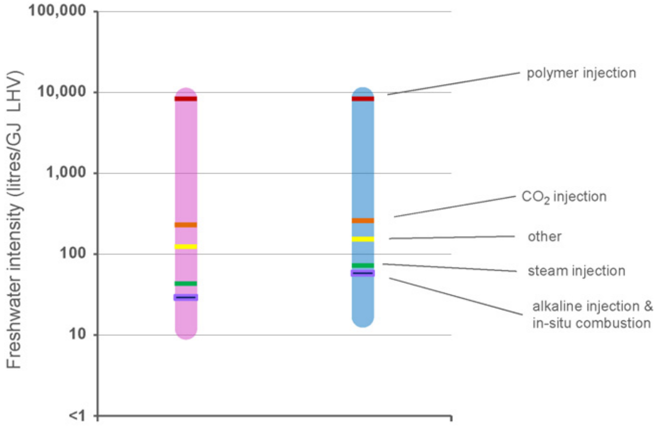


Fig. 8. Freshwater intensity averages for refined crude oil extracted with various tertiary-recovery technologies.

recovery. Commercial-scale cellulosic ethanol bio-refineries, however, are at an early stage of development (Wu et al., 2009).

In contrast, the "typical average" freshwater intensities of the biomass-to-biofuel supply chains of soybean, sugarcane and maize are two orders of magnitude larger than the average freshwater intensities of the oil-to-liquid fuel supply chain based on the primary recovery of crude oil and more than one order of magnitude larger than the average intensities based on the secondary recovery of crude oil. Even though the percentage of these crops' evapotranspiration met by irrigation does not exceed 6% (Mekonnen and Hoekstra, 2010), the large irrigation-water volumes needed by some sites within the region during certain stages of crop growth and/or prolonged droughts, push the *average* freshwater intensities in to higher levels. The "typical average" freshwater intensities of biofuels based on soybeans, sugarcane and maize are between 18 and 350 times higher than those of the same crops that have been "purely rain fed".

The freshwater intensities of biofuels depend heavily on the extent to which their source crops are irrigated. Globally, only 23.9% of agricultural land is irrigated (Portmann et al., 2010), although some irrigation is still required even in rain-fed regions. It should be borne in mind that higher freshwater intensities do not self-evidently result in freshwater stress; enough freshwater could be economically available.

For first-generation biofuels, the freshwater consumption-to-withdrawal ratios range from 0.4 to 0.6 for the biomass production and from 0.2 to 0.8 for its conversion to fuel. Second-generation biofuels have higher consumption-to-withdrawal ratios and lower freshwater intensities, since no water is allocated to the crop waste from which they are derived.

5.2.5. *Implications*

- Higher oil prices will render unconventional fossil fuels more economic; thus freshwater intensities for liquid fossil-fuel supply chains are – on average – likely to increase.
- In view of their possible long lifetimes, the specific energy technologies deployed in regions threatened by freshwater scarcity should be selected from those found in the lower part of the freshwater-intensity ranges. These ranges can vary by orders of magnitude from top to bottom. For example, gas-to-liquids plants can recycle produced water, bringing down freshwater withdrawals and consumption to zero – as is done at the Pearl GTL plant in Qatar. This stands in sharp contrast to the 150 l/GJ at the other end of the water withdrawal and consumption range for gas-to-liquid fuels.
- The predominance of freshwater intensities of oil supply chains is shifting from the downstream to the upstream. This is caused by increases in unconventional oil recovery – which has relatively high freshwater intensities – and decreasing freshwater withdrawal intensities of oil refining as refineries recycle process water more and increase their reliance on recirculating wet cooling at the expense of once-through cooling.
- The production of natural gas is less water-intensive than the production of other fossil fuels or biofuels. This holds true for unconventional shale gas too, even though freshwater withdrawals are relatively high in its preproduction phase. Site-level water accounting, both with regard to water volume and quality of the effluent, is essential to evaluate compliance with regulations.
- The combination of increasing demand for food and the manyfold growth in biofuels – the global use of biofuels in 2035 is expected to be almost four times higher than in 2009 (IEA, 2010) – will increase the pressures on crop yields and land productivity. To ensure these pressures do not lead to increases in average freshwater intensities of biofuels production, it is important that the best biomass (in terms of water use efficiency) and the best locations (rain-fed areas) are selected, while the best technologies (for irrigation and conversion) are further developed.
    - ○ Future freshwater-related risks of biomass production for fuels will largely depend on whether this growth will come from rain-fed or irrigated land. Other tradeoffs between irrigated and rain-fed land exist: a large part of the world's remaining cultivable rain-fed land is currently occupied by tropical rainforests (Ramankutty, 2010).
    - ○ Climate change may have significant impacts on agricultural systems through changing precipitation patterns, intensities and extremes. The freshwater resources that may be required for irrigation are also vulnerable to climate change. Regions irrigated with melt water from mountains, for example, may face reduced water availability as the volume of glaciers and snow cover decline over the course of the century (Bates et al., 2008).
    - ○ Small improvements in globally deployed irrigation technology and practice – through increasing irrigation efficiencies and decreasing crop evaporation in favour of transpiration for the same amount of biomass produced – may have important benefits because the freshwater intensities of irrigated agriculture are so large.
    - ○ Biomass-to-fuel conversion has much lower freshwater intensities than the procurement of the biomass feedstock – and they are decreasing. For crop residue feedstock, however, the crop water consumption is usually allocated to food production. Economic freshwater stress could thus possibly incentivise the co-production of food and second-generation biofuels.

5.3. *Results for electricity*

The freshwater withdrawal and consumption intensities for electricity generation are summarised in Fig. 9. Although included in our results, the freshwater intensities for resource extraction are generally negligible compared to the power plants' intensities. The only exceptions are natural gas combined-cycle power plants with dry cooling and coal-fed power plants. We disregarded the water intensities of the feedstock for biomass-fired power plants. Their feedstock consists mostly of waste generated by the forestry industry, farms or municipalities (Bracmort, 2011).

The withdrawal/consumption pairs are grouped by cooling technologies, because in most cases these have a greater influence on freshwater intensity than the plant's conversion efficiency or fuel. Within each cooling-system group, the intensities are arranged in increasing order of freshwater consumption so that the influence of conversion technologies can also be easily assessed.

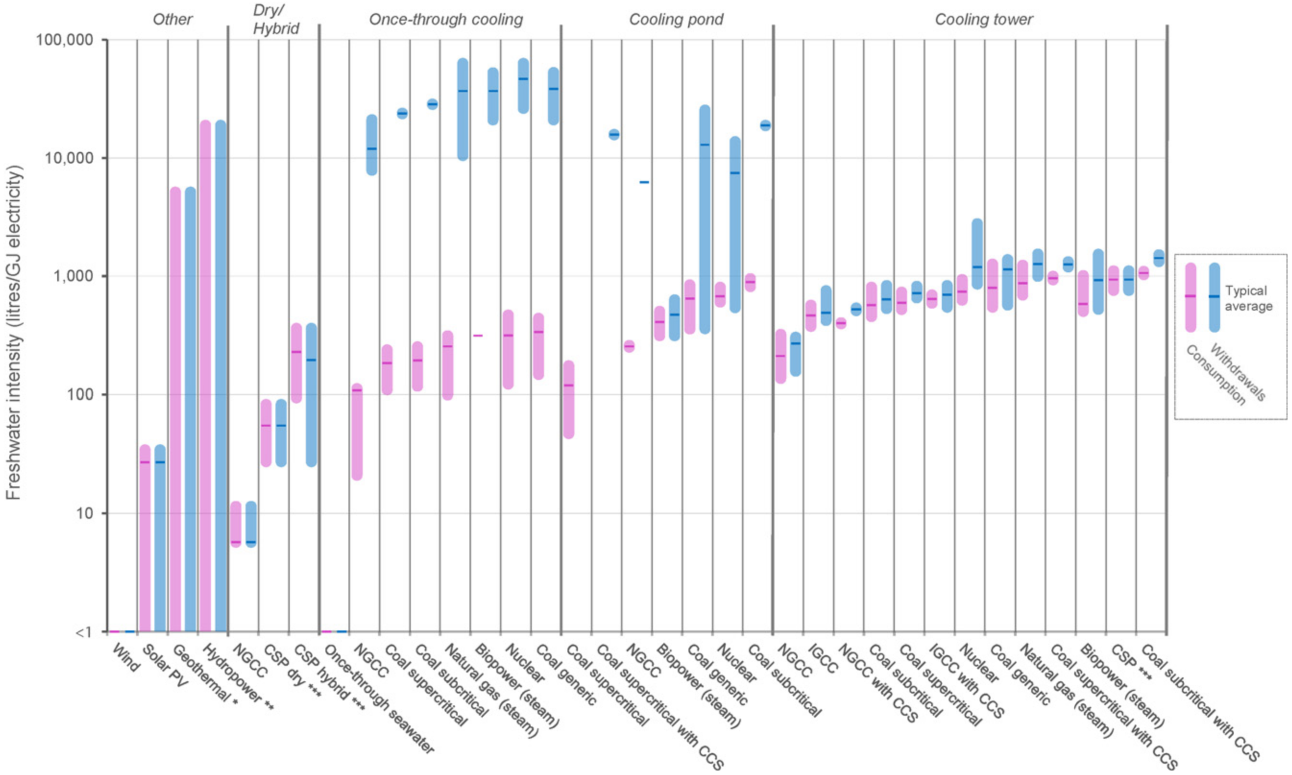


Fig. 9. Source-to-carrier freshwater intensities for electricity production (based on Macknick (2011); only hydropower from International Hydropower Association (2009)). CSP: concentrated solar power; IGCC: integrated gasification combined cycle; CCS: carbon capture and sequestration; NGCC: natural gas combined cycle. *Includes enhanced geothermal systems, binary, and flash geothermal technologies with recirculating, dry and hybrid cooling system technologies. **Highly location dependent; average not calculated. ***Includes trough, tower and fresnel technologies.

5.3.1. *Cooling system trade-offs*

The cooling system is an integral part of a power plant. Fig. 9 shows that freshwater withdrawals for recirculating wet systems are substantially lower than those of once-through cooling systems, but freshwater consumption is higher. For a given conversion technology, the median freshwater withdrawal intensity for cooling towers is 29–51 times less than that of once-through cooling systems, yet the median freshwater consumption intensity is between 1.8 and 4.2 times more.

Once-through cooling technologies need the highest freshwater withdrawals, followed in order by cooling ponds, cooling towers and dry cooling. Cooling towers result in the most freshwater consumption, followed in order by cooling ponds, once-through cooling and dry cooling.

Other significant trade-offs exist between selected performance indicators of cooling technologies for thermoelectric power plants. In Table 5 we have compiled important trade-off criteria – including capital costs – from a wide range of literature sources. These criteria need to be assessed on a site-by-site basis. For one thing, once-through cooling for new power plants in the U.S. has become exceptional as a consequence of the Water Pollution Control Act and the Clean Water Act.

Trade-offs of other sorts also exist between cooling technologies. Once-through cooling systems have been criticised for: endangering aquatic organisms living near the water intake; the environmental impact of warm effluent discharges; and the eyesore structures that are built on the coast lines in the case of seawater-cooling systems. Cooling towers can produce unsightly plumes on humid or cold days. Dry cooling systems may require more land than wet cooling systems.

5.3.2. *Conversion technologies*

Generating electricity with wind and solar photovoltaic (PV) systems certainly conserves water. Water-cooled concentrated solar power (CSP) technologies, however, have relatively high water intensities, making air-cooled CSP more suitable for inland desert areas, which offer plenty of land and sun (Macknick et al., 2011). In any case, solar and wind technologies account for a small minority of the world's power-generation capacity today.

Among fossil-fuel power plants, those based on conversion technologies with relatively high efficiencies, such as combined gas turbine/steam cycles and supercritical steam cycles based on coal, have relatively low freshwater intensities. Nuclear power plants have among the highest power-plant freshwater intensities, because they have a relatively low heat-to-power conversion efficiency. They apply single-cycle steam turbines operating at relatively low steam pressures and temperatures (for safety reasons).

5.3.3. *Carbon dioxide capture and storage*

Augmenting natural gas and coal-fed power plants with carbon dioxide capture and sequestration (CCS) technologies substantially increase water intensities. The CO_2-capture process itself uses water and the consequential reduction in overall plant efficiency also has an impact. Table 6 lists the percentage increases in the median freshwater intensities for typical power-generation technologies when CCS is implemented. The addition of CCS causes freshwater withdrawals to increase by 50–140% and freshwater consumption to increase by 45–100% (based on Macknick et al. (2011)). These percentages are similar to those in DOE/NETL (2008).

Table 5
Thermoelectric power plant cooling system trade-offs. The freshwater intensities in the first pair of columns depict the average freshwater intensity of all thermoelectric conversion technologies except once-through seawater. Energy efficiency penalties of fossil-fuelled power plants translate into CO_2 emission penalties. The trade-off data are deduced from Macknick et al. (2011), World Nuclear Association (2011), DOE/NETL (2008), Electric Power Research Institute (2007), Mielke et al. (2010), PIER/Electric Power Research Institute (2002).

Cooling system	Average freshwater intensity (l/GJ)		Efficiency penalty (%)	Capital cost penalty of applying other cooling technology	Capital costs ($/kW installed)	Other trade-offs		Number of fossil or biomass-fired plants in the U.S.	
	Withdrawal	Consumption				Advantage	Disadvantage	Pre-1970	Post-1969
Once-through	31,809	207	(Baseline)	Base: hypothetical 500MW steam power plant	19	High cooling efficiency; can use saline or brackish water	Intake entrainment; warm discharge	540	120
Wet recirculating – cooling tower	828	609	2–5	+0.4%	28	Reduced intake entrainment; cooler discharge	Plume formation; drift; larger land requirements than once-through	125	380
Wet recirculating – cooling pond	10,276	457	Not available	N.A.	27	Can use saline or brackish water	Larger land requirements than once-through	160	200
Dry recirculating	2	2	2–20	+12.6%	182	No intake entrainment	Larger land requirements than wet recirculating	10	10
Hybrid	20% of wet recirculating systems		Variable	N.A.	Variable	Flexible trade-off between energy and water conservation; no "hot day" penalty	Similar to dry and wet recirculating; limited technological maturity	N.A.	

The post-combustion amine-based CO_2-extraction process exacts a larger freshwater intensity penalty than the pre-combustion selexol process, because of its significantly higher cooling requirement (Black, 2010). Of the listed power plants, the NGCC with CCS has the lowest freshwater intensity although the CCS incurs a 96% and 91% penalty on its withdrawal and consumption. More energy-efficient CCS technologies are imaginable for the future, possibly resulting in a moderation of the freshwater intensity increases (Wesker, 2011).

5.3.4. *Implications for electricity generation*

- The selection of cooling systems and conversion technologies for power plants needs to take future freshwater scarcities and regulation into account, since the capital goods of thermoelectric power plants have long lifetimes. Local water costs should also be considered. Utility water costs comprise the cost of acquisition, the cost of delivery, and the cost of treatment and discharge (Electric Power Research Institute, 2007). Higher freshwater costs provide the incentive to deploy dry or hybrid cooling systems, or to generate power at the coast, where once-through seawater cooling is possible.
- The U.S. power industry's move from once-through cooling to wet recirculating cooling has shifted its water use from very high water withdrawals to relatively high water consumption. This shift also has resulted in increased capital expenditures for cooling systems.
- The increasing use of natural gas in the global power sector may result in a decrease of average freshwater intensities for electricity generation. An NGCC power plant can withdraw 50% less freshwater than a coal-fed subcritical power plant; it also can consume 67% less freshwater. Global gas-fired power generation grew by 60% in the last decade (IEA, 2011a), raising its share of global electricity from 18% to 22%.
- Wind and solar PV systems could significantly decrease the freshwater intensities of power generation. Considering the increasing awareness of freshwater constraints and the already existing concerns about CO_2 intensities, these electricity-generation technologies will probably become more attractive.
- CCS has a significant potential to decrease worldwide CO_2 emissions. However, widespread deployment of current CCS technologies could significantly increase freshwater withdrawals and consumption. Water-efficient CCS technologies should be developed for water-scarce areas.
- Energy policies can have significant impacts on average freshwater intensities of power generation. For example, before the Fukushima Daiichi disaster in Japan nuclear power accounted for 14% of global electricity production (IEA, 2010). Following the disaster, several countries shifted their energy policies, dimming the prospects for new nuclear power plants. Such plants have a relatively high freshwater intensity if they depend on wet recirculating cooling systems.
- Opportunities to reduce freshwater intensities lie in the use of low-quality water supplies for once-through cooling systems; wet recirculating cooling systems have higher water-quality requirements. Coastal power plants can take advantage of once-through seawater cooling, but other potential water sources are municipal effluents, industrial discharge water, agricultural runoff and brackish groundwater (Electric Power Research Institute, 2003).
- Freshwater intensities for hydropower generation are highly location dependent. Hence, figures for one region should not be applied to other regions. The development of hydropower projects needs in-depth assessments at the basin level to determine the potential effects to the local freshwater budget (International Hydropower Association, 2009).

Table 6
CCS freshwater-intensity penalties (based on Black (2010) and Macknick et al. (2011)).

Conversion technology with cooling tower	CCS technology	Withdrawal penalty	Consumption penalty	Water withdrawal[a] (l/GJ)	Water consumption[a] (l/GJ)
Coal supercritical	Post-combustion with amine absorbers	+84%	+71%	1262	965
Coal subcritical	Post-combustion with amine absorbers	+140%	+100%	1424	1066
Coal IGCC	Pre-combustion with selexol solvent	+50%	+ 45%	697	643
NGCC	Post-combustion with amine absorbers	+96%	+91%	270	212

[a] Freshwater intensities include CCS penalty.

6. Source-to-mobility freshwater intensities

The production of energy carriers is not an end in itself; they are used for services such as lighting and mobility (Goldemberg and Johansson, 2004). With the freshwater intensities for transport fuel manufacturing and electricity generation in hand, we were able to compare the freshwater intensities of different personal mobility pathways. Specifically, we compared driving in vehicles powered by internal-combustion engines with driving in those powered by electric motors. Fig. 10 shows the results based on the energy efficiencies listed in Table 7.

Electricity transmission losses between sources of supply and consumers vary widely around the world. About 4% of electricity output was lost during transmission in the Netherlands in 2008, whereas 52% was lost in Botswana. In this study we assumed transmission losses of 7% – equivalent to those in the UK in 2008 (The World Bank, 2011). World fuel distribution losses are less than 1% of total primary energy supplies (IEA, 2011b), and are thus considered negligible.

Table 7
Energy efficiencies used to determine source-to-mobility freshwater intensities.

Drivetrain	Efficiency (MJ/km)[a]
Gasoline (direct injection)	1.88[b]
Ethanol (direct injection)	1.88[b]
Biodiesel (direct injection, with diesel particle filter)	1.66[b]
Electric (battery electric vehicle)	0.49[c]

[a] All efficiencies are based on the standard New European Drive Cycle – the typical usage of a car in Europe.

[b] Based on simulations of a common "virtual" vehicle, representing a typical European compact size C-class 5-seat sedan comparable to a VW Golf (CONCAWE JRC EUCAR, 2008).

[c] Based on a C-class Nissan Leaf (Nissan, 2011).

Of the mobility pathways included in Fig. 10, those based on "conventional" electricity tend to have higher average freshwater intensities than those based on primary-recovery oil and refining. For those based on electricity generated with dry cooling technologies, solar PV or wind turbines, however, the opposite is true: they tend to have lower freshwater intensities. The average freshwater intensities of mobility based on electric motors powered by batteries charged with electricity from subcritical coal-fired plants are comparable to those based on internal combustion engines fuelled with refined oil from secondary or tertiary recovery (except

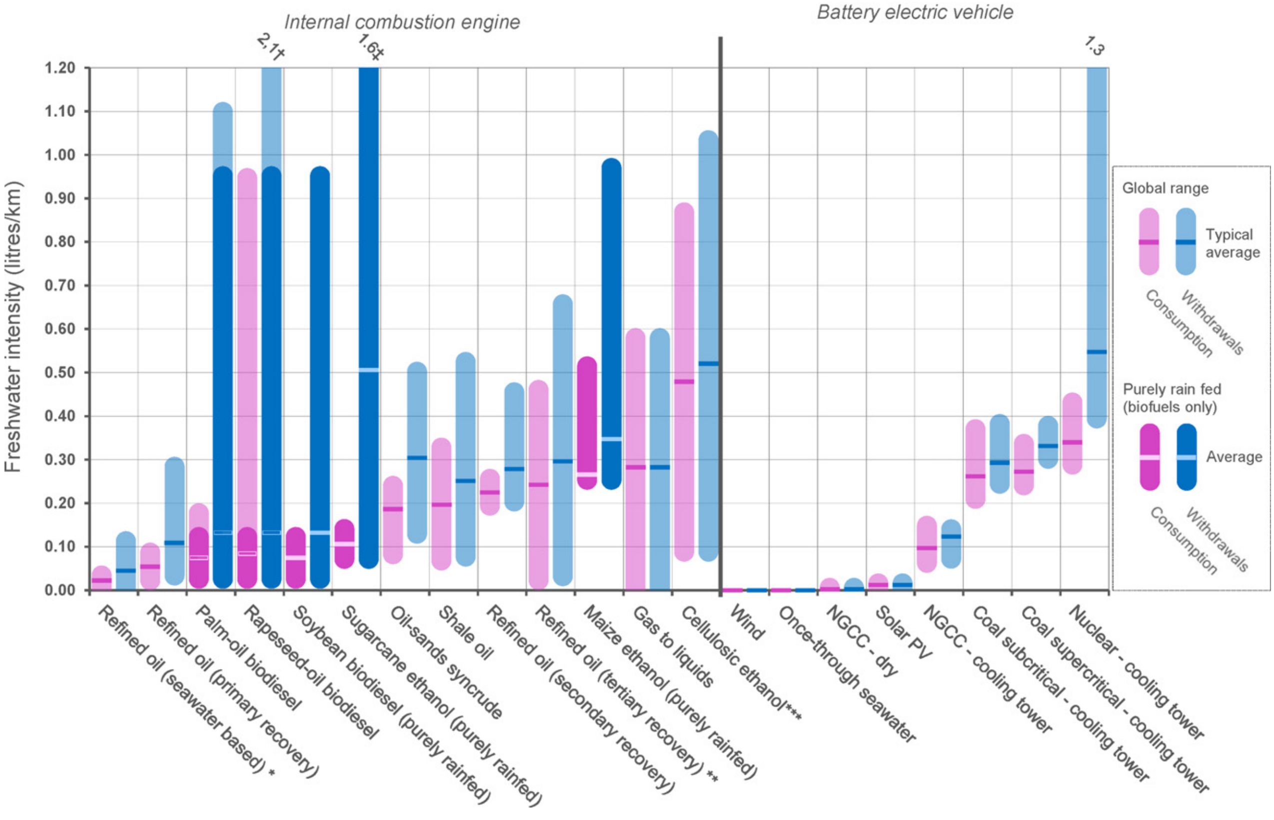


Fig. 10. Source-to-service freshwater intensity ranges and averages for mobility based on liquid-fuelled and electric-powered vehicles. *Based on seawater oil recovery and refinery once-through seawater cooling. **Excludes polymer-injection recovery technologies. ***Excludes water consumption for biomass growth, which is arbitrarily allocated to food production. †Based on national average of France for biomass production. ‡Based on national average of India for biomass production.

for polymer injection) or with shale–oil, oil–sands or gas-to-liquid fuels.

Some mobility pathways were excluded from the figure: those based on "typical average" biofuels from sugarcane, maize and soybean as well as those based on thermoelectricity with once-through cooling or cooling ponds. Their average freshwater withdrawals or consumption intensities are too large to capture on the linear scale of the chart. For example: average maize-to-mobility pathways need 11.6 l/km of water withdrawal and 6.4 l/km of water consumption; coal-to-mobility via a coal subcritical power plant with once-through cooling needs 13 l/km of water withdrawal and 0.09 l/km of water consumption.

6.1. *Implications for mobility*

- Policymakers supporting the electrification of mobility need to assess the potential impact on regional freshwater availability and quality. The impacts will largely depend on the electricity generation mix and the regional water stress levels. King and Webber (2008) concluded that the current U.S. technology mix results in electricity-based mobility pathways that withdraw 17 times more water and consume almost 3 times more water than mobility pathways based on gasoline.
- Changes in the relative drivetrain efficiencies between liquid-fuelled engines and electric motors as well as in electricity transmission losses will affect freshwater-intensity differences between electric and internal-combustion-engine transport.

7. Discussion

Water consumption and withdrawal data for industrial operations are often scarcely available and inconsistent. The terms "water intensity", "water use", "water needs", "water requirements", "water demands", "water intake", "water withdrawals", "water consumption" and "Water Footprint" have been applied interchangeably and without explicit definition.

Sound water-accounting methodologies have been developed on the basis of different perspectives, but none are suitable for application to industrial operations. The lack of a generally accepted water-accounting methodology has resulted in many misinterpretations in site-level and higher-level, aggregated studies.

This paper introduces a generic water-accounting methodology for industrial operations suitable for the analysis of emerging disruptive forces on water-using industrial operations. It enables water use to be recorded in terms of direct water withdrawal, consumption and discharge at both the industrial-site and supply chain or pathway levels. At the industrial-site level, various parameters (source type; volume; quality in terms of saline, brackish and freshwater; source; location; and time) need to be specified, because each of them can be influenced by local regulatory and resource constraints. At the pathway level the qualitative parameters cannot be specified, and thus the volume of freshwater withdrawals, freshwater consumption and gross water discharge reflect typical water use. Our proposed water-accounting methodology does not consider green water (consumed rainwater) as part of water-stress evaluation and is therefore not accounted for. Instead, the methodology favours the accounting of blue water (consumed surface and groundwater), which is functionally dependent on green-water availability in the case of agro-industrial operations.

The aggregated supply-chain and pathway freshwater intensities presented in this paper facilitate the selection of adaptations that reduce water-related risks or that capitalise on water-related opportunities associated with the provision of energy carriers and personal mobility services. However, caution is necessary when applying global conclusions to locally preferred industrial operations. The constraints under which companies must operate depend on the local water availability, the number of competing users, the quality of the discharges and the vulnerability of the local water system. Thus, the evaluation of operational risks posed by water resource and regulatory constraints requires the application of water accounting at both levels of aggregation simultaneously.

8. Future work

- Data related to site-level freshwater intensities – particularly water withdrawals for fuels and empirical data of withdrawals and consumption for biofuel supply chains – need to become more available in a way that conforms to our proposed generic industrial water-accounting methodology. As explained in the Supplementary Information, freshwater withdrawals for fuels were estimated on the basis of derived consumption-to-withdrawal ratios.
- The trade-offs in the various source-to-service pathways to mobility – between CO_2 emissions (grams emitted per kilometre driven) and freshwater intensities (litres withdrawn/consumed per kilometre driven) – need to be investigated in the context of climate-change mitigation policies.
- The tipping points at which innovative energy pathways with lower freshwater intensities become competitive should be investigated in scenarios with increasing prices or regulatory intervention for both CO_2 emissions and freshwater usage (i.e., withdrawals, consumption and discharge).
- Economical and ecological objectives must be specified integratively for energy pathway optimisations. Ecological objectives include not only reducing economic water stress but also reducing the carbon footprint, the land and ecosystem footprint and material intensities.
- The water productivity (value added per litre of water withdrawn/consumed) of energy technologies and water-availability cost curves (e.g., desalination, cascading, recycling as well as enhanced irrigation and cooling technologies) should be investigated for water-stressed basins. This way, water resource management can be integrated into economic strategies.
- The long-term implications of freshwater withdrawal and consumption forecasts for energy carrier production in specific regions and water basins should be determined on the basis of the new data and a generally accepted methodology. Energy technologies that account for large withdrawals can be identified in advance, as can the regions where water stress is likely to take serious forms. A next step would be to also include withdrawals needed for agricultural, municipal and other industrial operations together with water availability to determine future scenarios of regional freshwater stress.

Acknowledgements

We thank Gregory Greenwell for thorough and extensive editing; Deepa Varma, Veronika Dornburg and Jan Werner for helpful input and comments on the biofuels section; and Joppe Cramwinckel, the World Business Council for Sustainable Development and the participants of the water-energy-food-climate nexus workshops for providing a valuable platform for dialogue.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2011.12.011.

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