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ENVIRONMENTAL IMPACTS OF CONTRASTED GROUNDWATER PUMPING SYSTEMS ASSESSED BY LIFE CYCLE ASSESSMENT METHODOLOGY: CONTRIBUTION TO THE WATER–ENERGY NEXUS STUDY[†]

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ABSTRACT

Most studies on the environmental performance of irrigation have focused on the water–food–energy nexus, i.e. relationships between food production, water consumption and energy. However, water and energy are not the only relevant indicators of the environmental performance of irrigation systems. Life cycle assessment (LCA) is a holistic method that is well suited to comprehensive assessment. This paper aims at using LCA to assess the environmental impacts of contrasted groundwater pumping systems in semi-arid central Tunisia.

In line with previous studies, our results confirm that for groundwater pumping, energy has the highest environmental impacts on human health, the ecosystem and resource depletion. Our work also highlights that along with pump efficiency, the type of power source must be considered when ranking pumping systems based on environmental performance.

Indeed, diesel-powered pumping systems are more harmful than electric pumps when electricity is generated from natural gas and diesel-powered pump efficiency is low. However, the diesel pumping system becomes the best option when electricity is derived from coal and diesel-powered pump efficiency exceeds 12%.

Finally, water depletion has been shown of great importance in this study, and ongoing LCA improvements should facilitate a more comprehensive picture of these site-specific impacts. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: groundwater irrigation; energy; greenhouse gas emissions; water depletion

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RÉSUMÉ

La plupart des études sur la performance environnementale de l'irrigation ont mis l'accent sur le lien eau–alimentation–énergie, c'est à dire, les relations entre la production alimentaire, la consommation d'eau et d'énergie. Cependant, l'eau et l'énergie ne sont pas les seuls indicateurs pertinents de la performance environnementale des systèmes d'irrigation. L'Analyse du Cycle de Vie (ACV) est une méthode holistique adaptée à l'évaluation globale. Cet article vise à utiliser l'ACV pour évaluer les impacts environnementaux de systèmes contrastés de pompage d'eau souterraine, en zone semi-aride, au centre de la Tunisie.

En accord avec les études antérieures, nos résultats confirment que pour le pompage des eaux souterraines, c'est l'énergie qui domine les impacts environnementaux sur la santé humaine, les écosystèmes et l'épuisement des ressources. Notre travail met également en évidence que pour classer les systèmes de pompage selon leurs performances environnementales, il faut prendre en compte non seulement l'efficience du système de pompage mais aussi le type d'énergie utilisée.

En effet, les systèmes de pompage alimentés au diesel sont plus nuisibles que les pompes électriques lorsque l'électricité est produite à partir du gaz naturel et que l'efficience de la pompe est faible. Cependant, le système de pompage alimenté au diesel devient la meilleure option dès lors que l'électricité est produite à partir de charbon et l'efficience de la pompe dépasse 12%.

Enfin, les impacts sur l'épuisement en eau se sont révélés très importants dans notre cas d'étude et les avancées méthodologiques en cours permettront d'affiner la modélisation de ces impacts de type locaux. Copyright © 2014 John Wiley & Sons, Ltd.

MOTS CLÉS: irrigation à partir d'eaux souterraines; énergie; émissions de gaz à effet de serre; épuisement en eau

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[†] Impacts environnementaux de systèmes contrastés de pompage d'eau souterraine, évalués par la méthode d'Analyse de cycle de vie: Contribution à l'étude du Nexus eau-énergie.

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INTRODUCTION

Groundwater is intensely exploited to support irrigated food production worldwide (Bouarfa and Kuper, 2012). At present, of the 300 million ha of irrigated land worldwide, some 111 million depend on groundwater, which represents 25% of the total irrigation water (Siebert *et al.*, 2010). Although groundwater irrigation increases water productivity, it also has several adverse impacts: input intensification, high energy requirements for water pumping along with significant water depletion. Private and uncontrolled access to this shared resource raises the question of irrigation sustainability (Llamas, 2005; Shah and Cott, 2007; Kuper *et al.*, 2012). Therefore, it is of prime interest to assess the environmental performance of groundwater irrigation systems and especially of individual pumping systems. Up to now, this question has focused on the water–food–energy nexus (Mukherji, 2007; Shah and Cott, 2007; Hoffman, 2010; Olsson, 2012), which addresses the issue of relationships between food production, water consumption and energy. These relationships have been studied using holistic approaches to avoid environmental impact shifting between water and energy (USDOE (US Department of Energy), 2007; Molden, 2007; International Water Association (IWA), 2010; United Nations, 2013). Indeed, groundwater irrigation leads to increased water withdrawals from water bodies, and consequently to groundwater table decreases, when water withdrawals exceed water replenishment (Wada *et al.*, 2012). Moreover, irrigation is an energy-intensive practice: it is estimated that up to 50% of the total energy input at farm level is used to power the irrigation pumping set (Batty and Keller, 1980; Khan and Singh, 1997; Lal, 2004; Canakci and Akinci, 2006; Hatirli *et al.*, 2006). Finally, energy consumption significantly contributes to greenhouse gas emissions (Jackson *et al.*, 2008, 2011; Mushtaq *et al.*, 2013).

Adopting a life cycle approach, Tyson *et al.* (2012) proposed a framework to account for the energy requirements and related greenhouse gas emissions of pumping systems. These authors showed that depending on the environmental criteria used, pumping systems obtained different performance levels and no single system emerged as the optimal solution.

To broaden the environmental assessment of groundwater irrigation and prevent any burden shifting we have adopted the life cycle assessment (LCA) methodology (Guinée *et al.*, 2011). LCA methodology has already been used to address water depletion issues related to irrigated crops (Pfister *et al.*, 2009; Mila i Canals *et al.*, 2010; Roches *et al.*, 2010). In these studies, the water–energy nexus was certainly not the main issue and the contribution of the irrigation system could not be distinguished from that of the agricultural system itself.

The objective of this paper is to carry out an LCA study on various irrigation systems with a focus on pumping technologies independent of any crop-related issues. Our work is specifically devoted to the pumping system set. We concentrate on parameters identified by Jackson *et al.* (2011), i.e. the suction head (mainly linked to groundwater table depth) and pump efficiencies, while neglecting other parameters such as those related to the cropping system, irrigation technology and the climate.

Our case study concerns the Kairouan alluvial aquifer in semi-arid central Tunisia. Various pumping systems coexist: former open wells that have been deepened and more recent deep boreholes. These systems are equipped with surface and submersible pumps.

In this paper, we first describe the case study in the Kairouan Plain, Tunisia, and in particular the four types of pumping systems. Later, we present the LCA methodology and the computations required to generate the required life cycle inventory (LCI). The relative contributions of each of the pumping system components will be examined, i.e. the infrastructure, the pump and the power source. An analysis of the sensitivity of LCA results to groundwater table depth, power source and (diesel) pump efficiency will be carried out to broaden the relevance of this research to other geographical and technological contexts.

MATERIALS AND METHODS

Study area

This study was conducted in Tunisia, in the 2011–2012 crop production year in the central region of Kairouan, a semi-arid to arid region. Annual rainfall ranges from 180 to 420 mm with an average of 300 mm. The calcareous Kairouan aquifer is the largest of the region and these favourable conditions have led to the significant development of irrigated farming over the whole region. Conditions in the area under study are representative of those commonly found in regions where groundwater overdraft, a worldwide phenomenon, occurs: the groundwater table depth is 35 m and currently falling at an annual rate estimated at 1 m at least. In spite of regulations implemented in 1990 aimed at prohibiting any new borehole within a protected area, borehole drilling has not ceased, and the groundwater table has continued to fall (Leduc *et al.*, 2004). However, groundwater table accessibility varies among farmers. This depends on their economic status. Wealthy farmers will invest in deep borehole drilling (up to 150 m) to secure their access to water over time and against significant drawdown due to high withdrawals. During seasonal peaks in irrigation demands, the groundwater table drawdown is so severe that there is a drop in the flow rates of shallow tube wells, which provide water to poorer farmers.

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LCA methodology

LCA is a standardized method whose first applications date back to the early 1990s. Latest standards were drawn up in 2006: ISO 14 040 and 14 044. With this method, the potential impacts on the environment of the production of a given product or service (called the functional unit) are calculated based on cause–effect chains. This is a four-step method. First, the goal and scope of the study must be defined: the functional unit, the methodological choices and system boundaries are set. Subsequently, the system producing the functional unit is modelled and input (materials, energy, water, etc.) and output (polluting emissions) flows are listed for the entire life cycle of the studied product (or service) from raw material extraction to its end-of-life disposal (cradle to grave approach). This is the life cycle inventory, or LCI, which is the second phase of LCA. Throughout the causality chains, input and output flows are converted into impacts, using so-called characterization factors. Impacts can be either at midpoint level (e.g. climate change, ozone depletion, eutrophication) or at endpoint level, i.e. damage to three major areas of protection (ecosystems, human health, resources). This third phase is called life cycle impact assessment (LCIA). Results may be normalized, and/or weighted against references values. As a wide range of impacts are assessed, LCA avoids the pitfall of shifting impacts from one category to another, which is the drawback of many other methods focusing on one or a few impacts. Likewise, the life cycle perspective prevents the shifting of impacts from one life cycle stage to another. The fourth and final LCA step is the interpretation phase. LCA results are analysed and discussed for different purposes depending on the goal and scope (first step) of the study: ecodesign, technology benchmarking, ecolabelling, communication, etc.

For the LCA practitioner, a LCA mainly involves modelling the production system required to provide one functional unit; each component or process is broken down into elementary processes, of which the LCI is well known (available in databases of elementary LCI (e.g. Ecoinvent) generated using LCA software) or may be easily computed.

Several methods are available to compute impacts (LCIA step), either at the midpoint or endpoint level of the cause–effect chain. The ILCD (international reference life cycle data system) is the method recommended by the European Commission (2010) to generate midpoint impacts. As we aim to analyse environmental impacts at midpoint and endpoint levels, we chose the Recipe 2008 LCIA method which provides both sets of information (Goedkoop and Huijbregts, 2012). The other advantage of this method is its comprehensiveness regarding impacts along with its relative compatibility with older methods such as CML (Guinée *et al.*, 2001), which was commonly used in the past for agricultural LCA.

Figure 1 presents the global framework of the LCIA method 'Recipe 2008'. It displays the cause–effect chains,

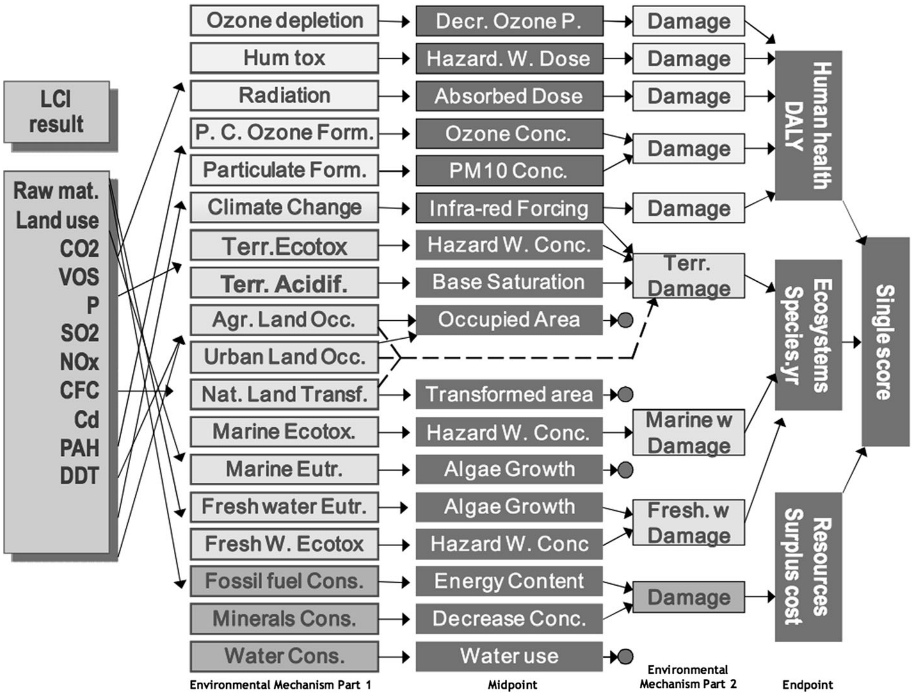

Figure 1. Life Cycle Assessment methodology framework « Relationship between LCI results (left), midpoint indicators(middle) and endpoint indicators (right) » in ReCiPe 2008 from (Goedkoop and Huijbregts, 2012)

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i.e. the inventory results which are converted into impacts by environmental mechanisms at midpoint and endpoint levels. Indeed, the 18 Recipe midpoint impacts are subsequently aggregated into three endpoints of damage: human health, expressed in 'disability-adjusted life years' (DALY), ecosystems 'health' (in species.yr), and resources depletion (in dollars) required to restore resource provision. Climate change is the only midpoint impact which contributes to more than one endpoint category, namely human health and ecosystems.

The goal of this LCA study is to assess the environmental impacts of four pumping systems, which are representative of the Kairouan Plain. The functional unit is 1 m^3 pumped at a 35 m depth, 2 bars of pressure, and 0.9 bars of friction losses in pipes. LCA was performed with Simapro 7.3.0 LCA software, using the Recipe 1.07 (H) LCIA method and the EcoInvent 2.2 inventory database.

The typology of pumping systems

A 'pumping system' has three components: (i) the well or borehole infrastructure, (ii) the pump and motor equipment (submersible or not), and (iii) the power source (diesel or electricity from grid).

Figure 2 illustrates the diversity of water pumping system sets (PS in the following) identified in the study area. PS1, 2 and 3 are former open wells that have been used over 15 years on average before the groundwater table decline obliged farmers to deepen them manually with a tubewell. The pump type depends on the depth of the tubewell depth (suction +elevation head): surface pumps (PS1 and 2) are used in tubewells whose depth is 20 m and submersible pumps are exclusively used in 30 m depth tubewells (PS3 on Figure 2).

For PS 1 and 2, tubewell lifetime is limited to 5 years on average, due to the annual rate of groundwater table decline and the fact that surface pumps cannot draw water from below 7 m depths. Thus, considering that the open well was dug earlier and will last about 20 years, only 5 years of its lifetime (25%), is spent in PS 1 and 2.

For PS 3, the lifetime of the tubewell infrastructure is set at 20 years, assuming an annual groundwater table decline of 1.5 m. Of the 35 years of total open well use (15 years as a well +20 years as a tubewell), PS3 will only account for 20 years.

PS 4 is a borehole equipped with a submersible pump; it is generally drilled to 120 m depth, but it can reach 150 m. Infrastructure lifetime is assumed to be 30 years based on farmer declarations during field inquiries.

The standard diameter of PVC pipes is 7.62 cm (3 inches). Several characteristics that are relevant for LCA purposes are given in Table I for the entire pumping system infrastructure characteristics.

The annual operating time for each type of pump is determined through field observations: on average, people operate pumping systems 12 h day^{-1} during 6 months and 24 h day^{-1} during 6 months, i.e. 6570 h yr^{-1}.

Based on a field survey, pump lifetimes for submersible pumps is generally 10 years and 2 years for surface water pumps respectively. These results have been compared with pump supplier data. As the latter suggests 29 000 h of total lifetime, we adopt a conservative approach and retain this

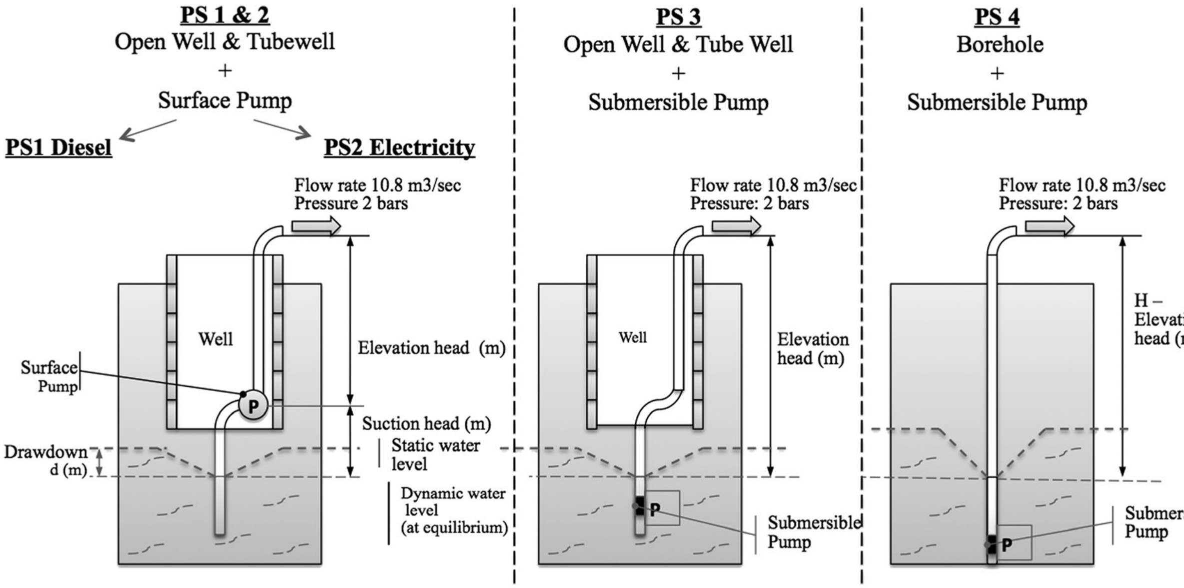

Figure 2. Four pumping systems sets identified in the alluvial plain of Kairouan-Central Tunisia. Old open wells are deepened by some farmers (PS1 to 3) while others invest in deep boreholes (PS4)

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Table I. Pumping system characteristics: well/borehole installation, pump materials and energy requirements for construction vary significantly

Pumping system	PS1	PS2	PS3	PS4
Infrastructure	Open well+ tubewell	Open well+ tubewell	Open well+ tubewell	Borehole
Depth of open well (m)	30	30+	30	120
Length of tube well (m)	20	20	30	–
Estimated friction losses/pipe friction (bars)	0.85	0.85	0.48	0.48
Delivered service pressure (bars)	2	2	2	2
Open well lifetime (yr)	15 (+5)[a]	15(+5)[a]	15(+20)[a]	0
Tubewell lifetime (yr)	5	5	20	0
Borehole lifetime (yr)	0	0	0	30
Pump power source	Diesel	Electricity from grid	Electricity from grid	Electricity from grid
Pump type	Surface	Surface	Submersible	Submersible
Flow rate ($m^3\,h^{-1}$)	10.8	10.8	10.8	10.8
Pump lifetime (yr)	2	2	4.4	4.4

[a] Lifetime is total lifetime, whereas the figure within brackets is the additional lifetime after well deepening for tubewell purposes.

value, i.e. 4.4 years for 6570 h (annual) operating time. For surface pumps, maintenance requirements are also considered with a replacement rate of about 0.2–0.8 of the total weight of the pump or engine over their lifetime (seals kit, moving parts, etc.). This has to be accounted for in LCA so that the total quantity of materials used and energy required over the life cycle is reported in the inventory.

Energy consumption computation: unit energy required for the different pumping systems

For the energy requirement inventory, the unit energy (in $J\,m^{-3}\,m^{-1}$) is computed, i.e. the energy (J) required to pump $1\,m^3$ of water in each of the different pumping systems.

The unit energy is computed, with regards to the hydraulic energy, using ŋ, as the efficiency of the pumping system such that

$$E_{\mathrm{req}} = E_{\mathrm{hydr}} \cdot ŋ^{-1} \qquad (1)$$

where ŋ is the global efficiency of the pumping system expressed in Equation (2).

The global efficiency, ŋ, is a combination of the efficiencies of the pumping system components (pump, the transmission and the motor):

$$ŋ = ŋ_{\mathrm{pump}} \cdot ŋ_{\mathrm{trans}} \cdot ŋ_{\mathrm{motor}} \qquad (2)$$

Hydraulic energy can be computed from hydraulic power:

$$E_{\mathrm{hydr}} = P_{\mathrm{hydr}\,.}\, t \qquad (3)$$

Hydraulic power is calculated based on the water flow and total dynamic head (Equations (4) and (5)):

$$P_{\mathrm{hydr}} = \text{pressure} \times \text{flow rate} = \rho\, g\, \mathrm{TDH}\, Q \qquad (4)$$

where ρ =fluid density ($kg\,m^{-3}$), g =gravity (=9.81 $m\,s^{-2}$), Q =flow rate ($m^3\,s^{-1}$) and TDH =total dynamic head (m).

$$\mathrm{TDH} = \mathrm{Hg} + J + P_{\mathrm{s}} \qquad (5)$$

where Hg =suction head +elevation head (m), J =friction losses (in the pipes, elbows, valves) (m) and P_s =output service pressure required (bar).

The time for pumping $1\,m^3$ is $t = VQ^{-1}$ with $V = 1\,m^3$, i.e. $t = Q^{-1}$. Therefore, from Equations (1), (3) and (4), the unit energy E_u is $E_u = \rho\ g\ \mathrm{TDH}\ Q\ t\ ŋ^{-1}$ with $t = Q^{-1}$:

$$E_{\mathrm{u}} = \rho\, g \mathrm{TDH}\, ŋ^{-1} \qquad (6)$$

With 100% efficiency, $E_u = 9810\,J$.

Energy consumption computation: inventory for the different pumping systems

Computing energy consumption requires flow rates, pumping system efficiency levels and groundwater table depth.

The values of groundwater table depth and flow rate were obtained from a survey carried out in 2010 by the regional administration of agriculture (non-published data). In addition, six values of water flows were determined in the field by measuring the time required to fill a recipient of known volume. Flow rate values were also checked against previous measurements dated 2004 and against expert knowledge, i.e. local extension officers. Friction loss values were calculated based on straight pipe lengths, bends, change of sections close to the pump and a valve (Schmitz, 2013).

For diesel-powered pumps, the global efficiency of the pumping system was deduced from the fuel consumption per hour declared by farmers and from a calculation of the hydraulic energy required. The fuel consumption rate per

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hour is considered robust data since the same value was given in almost all enquiries. The lower heating value of diesel was considered as 43 MJ kg^{-1} (Zegada-Lizarazu *et al.*, 2010). Indeed, knowledge of diesel consumption and running time for this specific pumping system enabled calculation of the unit energy required.

For surface pumps powered by electricity, energy requirements were deduced from the efficiency and the hydraulic energy (cf. Equation (5)). Pump efficiency was extracted from the performance curve characterizing performance for each pump. Firstly, the total dynamic head is expressed as a function of the flow rate and secondly, pump efficiency is displayed as a function of the flow rate. The approach was to ensure that the first curve estimating TDH matched the corresponding value for flow rate and subsequently to translate the corresponding pump efficiency on the second curve. Efficiencies for motor and direct transmission were taken from the literature (Batty and Keller, 1980; Luc *et al.*, 2006) and are set at 85 and 100% respectively.

The global efficiency of a submersible pump set at 50% was found in the literature (Hamidat *et al.*, 1998), and then validated by expert knowledge.

Sensitivity analysis

We would like our analysis of environmental impacts from typical Tunisian pumping systems to be applicable to other geographical and technological contexts, with regard to changes in groundwater table depth, power sources, irrigation pressure, as well as diesel pump efficiency.

First, we examined the relative damage contribution of each component of the pumping system by varying the total dynamic head from 64 m (baseline) to 14 m. This corresponds to a shallow groundwater table—of 5 m depth—and a surface irrigation technique, i.e. 0 bar at ground level.

Second, we studied the sensitivity of LCA results to the type of power source as well as the global efficiency of the diesel-powered pumping system (PS1). Indeed, in our Tunisian case study, electricity is mostly generated from natural gas, which is the least polluting fossil fuel (Phumpradab *et al.*, 2009). The baseline Tunisian electricity mix is generated with 88.7% of natural gas, 10.8% of petroleum products, 026% of hydropower and 0.27% of renewable power sources (Itten *et al.*, 2012). Three other power sources from the EcoInvent database, Simapro 7.3.0, were included in the sensitivity analysis, namely, 'electricity EU 27', 'electricity from coal' and the photovoltaic country mix from the Netherlands. 'Electricity EU 27' was chosen as it is a European average. 'Electricity from coal' as it is used in various countries, is a heavy polluter. Finally, one of the most harmful photovoltaic country mixes was included to provide an example of a renewable source of energy. The 'EU 27 mix' composition is: 317% nuclear power, 18.3% hard coal, 17% natural gas, 11.3% brown coal, 11.1% hydropower, 6% heavy fuel oil, 1.1% wind, and others (European Reference Life Cycle Database (ELCD), 2012).

The diesel-powered pumping system (PS1) proved to be very inefficient (due to local technologies and practices), i.e. 8%. Other studies indicate 28% (Tyson *et al.*, 2012). We therefore decided to extend the diesel pump efficiency to the value proposed by Tyson *et al.*, i.e. 28%, and to assess impacts of an intermediate value that is twice the baseline, i.e. 16%. Consequently, the unit energy required is respectively: 35 036 J when efficiency is 28%, 61 313 J when it is 16% and 122 625 J when it is 8%.

RESULTS AND DISCUSSION

Inventory of materials use for pumping systems (infrastructure and pump)

The inventory focused on:

- The materials and energy required for transportation, building, fixing the infrastructure elements, i.e. the open well, the tubewell, and the borehole (Table II), pumps and motor (Table III);

Table II. Life cycle inventory of the infrastructure required to gain access to the groundwater table

	Open well 30 m	Tubewell 20 m, 5 yr	Tubewell 30 m, 10 yr	Borehole 120 m, 30 yr
Concrete blocks (kg)	51 300	NA	NA	NA
Concrete, sole plate and foundation, at plant (m^3)	6	NA	NA	NA
Reinforcing steel, at plant (kg)	650	NA	270	1096
Fuel consumption for drilling (kWh)	50	27.5	77	NA
Electricity consumption for drilling (kWh)	NA	NA	NA	220
Gravel, round, at plant (kg)	NA	NA	NA	1750
Transportation (T km^{-1})	1040	20	54	562
PVC pipe E (kg)	150	100	NA	NA
Operating time (hr)	6570 yr^{-1}	32 900	65 700	

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Table III. Life cycle inventory of the pumping equipment. Values for one single pump of each type

	Surface pump			Submersible pump
	Thermic motor	Electric motor	Pump itself	
Total weight (kg)	56	56	52	58
Repair coefficient	0.8	0	0.2	0
Cast iron (kg)	0	40	37	0
Steel (kg)	50	12	19	0
Aluminium (kg)	50	0	0	0
Bronze (kg)	0	0	6	0
Copper (kg)	0	4	0	13
Stainless steel (kg)	0	0	0	100
Rubber (kg)	0	0	0	12
Transportation (kg km)	8 960	11 200	2080	25 000
Operating time (h)	13 140	13 140	13 140	29 000

- The energy consumed to draw water from the groundwater table to the surface.

The values are based on the case study; groundwater table depth is 35 m and output pressure is 2 bars.

We consider that open wells have been drilled with diesel-powered drilling equipment. The external well diameter is 3 m and walls are made up of concrete blocks, 0.2 m width, including 'bond beams' (steel reinforced concrete) every 2 m.

The deepening of open wells to form tubewells is assumed to have been performed manually (using small hand tools) to a maximum depth of 30 m.

Boreholes have been drilled with electric powered drilling equipment. The total duration of a 120 m depth borehole drilling operation was estimated at 46 h and required about 800 MJ of electricity. The borehole is equipped with a stainless steel strainer under the groundwater table level and stainless steel piping above the groundwater table. This system is isolated from the aquifer by gravel. All items are considered to have been transported by truck from the capital, 200 km from the study site, using an average fleet of 3.7–16 t trucks.

Pumping energy requirements

Table IV presents the results of unit energy (i.e. energy required to pump 1 m^3 for 1 m for each pumping system according to its global efficiency). With a 100% global efficiency rate, the required energy would be approximately 9800 $J\,m^{-3}\,m^{-1}$.

Global efficiency is estimated at 8% for PS1 (after calculation and data collected in field surveys), 50% for PS3 and 4 (from the literature), and 34% for PS2, i.e. the product of motor–transmission–pump efficiency levels, based on field measurements for the pump and on literature for motor and transmission (Luc *et al.*, 2006).

The energy required to pump 1 m^3 of groundwater is greatest for diesel-powered pumps, significantly lower for surface electricity-powered pumps and most energy efficient for submersible pumps, which is in keeping with other studies (Tyson *et al.*, 2012). However, the efficiency values obtained in the course of our case study are lower than those of Tyson *et al.* (2012). They assume global pump efficiency at 80%. Moreover, they obtained 28% global efficiency for diesel-powered pumps, which is almost four times higher than our 8% value based on field measurements.

Comparison of LCA results/environmental impacts of contrasted water pumping systems

Figure 3 presents the LCA results for the four pumping systems in the baseline situation. This computation was based on the functional unit, i.e. pumping 1 m^3 in a groundwater table at 35 m depth and providing a flow pressure of 2 bars.

In LCA, results from different impact categories have different units, e.g. 'kg of CO_2 equivalent' for climate change or 'kg of CFC11 equivalent' for ozone depletion. To make the categories commensurate, standard category units must be defined: when different systems are compared,

Table IV. Unit energy required in each of the four pumping systems sets to pump 1 m^3 1 m of total dynamic head expressed in $J\,m^{-3}\,m^{-1}$ and $Wh\,m^{-3}\,m^{-1}$

Pumping system set	1: Diesel- powered surface pump	2: Electricity- powered surface pump	3 and 4 : Electricity- powered submersible pump	Theoretical hydraulic energy
Global efficiency	8%[a]	34%[a,b]	50%[b]	100%
Unit energy required: in $J\,m^{-3}\,m^{-1}$	123 000	28 900	19 600	9 810
in $Wh\,m^{-3}\,m^{-1}$	34	8	5.5	2.7

[a] Based on field measurements;

[b] based on the literature and expert knowledge.

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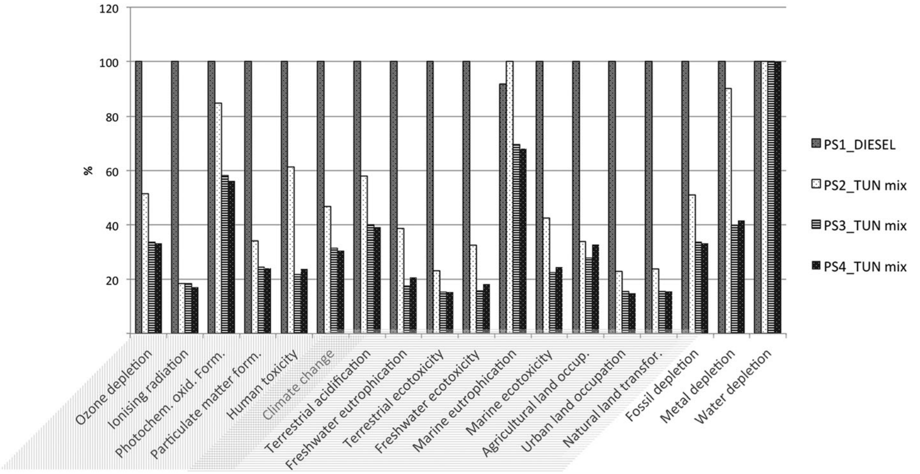

Figure 3. Midpoint LCA results for the pumping of one cubic meter (35 m depth, pressure at plot: 2 bars) using various pumping systems sets, powered either with diesel or with the Tunisian electricity mix, Recipe 1.07 (H)

the greatest impact in each category is set to the maximal value (100%). Each system is then presented relative to this 100% value. Among the 18 midpoint indicators displayed in Recipe, the first 6 contribute to human health damage, whereas the climate change midpoint impact plus the next 9 contribute to ecosystem impacts, and the remaining 3 are linked to resource depletion.

It is worth noting that, whatever the infrastructure, i.e. either open well and tubewell or borehole, submersible pumps (PS3 or 4) have very similar impacts, representing less than 5% difference. The pumping system hierarchy is identical over all categories of impacts except marine eutrophication, i.e. the diesel-powered pump (PS1) is the most harmful system for the environment followed by the electricity-powered water pump (PS2) and lastly the submersible pump, which poses the least threat to the environment (PS3 and PS4).

Pump lifetime and efficiency are two parameters that may explain why PS3 and PS4 impacts are much smaller than those of PS1 and PS2. Pump lifetime is about twice as long in PS3 and PS4 as in the others. But results are similar when lifetimes of PS3 and PS4 are set to the same value as for PS1 and PS2, i.e. 2 years. Indeed, the hierarchy is identical and unsurprisingly, the share of PS3 and PS4 increases by 20 points for metal depletion due to the extra amount of metal required when lifetime is reduced.

We should also note that the water depletion impact value is 100% whatever the pumping system, i.e. it is non-discriminating, because all of the systems are assessed for 1 m^3 of water pumped, and the pumped water is the main impact source of this category.

The climate change impact is far greater for PS1 than for PS2, PS3 and PS4. This is, of course, due to the power source, i.e. diesel combustion which emits much more greenhouse gas per MJ.

Impacts on climate change are less significant for electricity surface pumps than for diesel-powered pumps while the lowest impacts are obtained for submersible electricity-powered pumps. These results are at odds with Tyson *et al.*'s (2012) findings. These authors showed that diesel-powered pumps emitted less greenhouse gases than electric pumps, with either an Indian or Australian electricity mix. This discrepancy among results may originate from the very different electricity mix composition or from the differing performance levels of diesel pumps. The electricity mix is made up of 89% of natural gas in Tunisia, and of a majority of coal in Tyson *et al.* (2012). Diesel pump efficiency is more than three times better in Tyson *et al.* (2012).

The same hierarchy of impacts of pumping systems applies regarding 'fossil depletion' and 'particulate matter formation' which relates to pollution emitted during processing and combustion of fossil fuels. Metal depletion is higher for PS1 and PS2 due to shorter pumping system lifetimes and therefore higher amounts of metal used over the lifetime, for comparable weights. Indeed, the 2-year lifetime of a surface pump compares unfavourably with the 10-year lifetime obtained for submersible pump; moreover 20% of the surface pump and 80% of the combustion engine are replaced over the pump's lifetime.

While midpoint indicators are very useful for ecodesign purposes, endpoint indicators can provide a more extensive picture of the systems' performance levels with regards to the three areas of protection considered in LCA protection areas (cf. Figure 4).

The hierarchy at endpoint level remains the same as that obtained at midpoint level. PS3 and PS4 have similar impacts and have much lower impacts than PS1 and PS2.

The impact share is relatively steady over the three endpoints. PS3 and PS4 are on average 60% of PS2, which is itself half of PS1. The least energy-efficient pumping (PS1) generates three times the impact levels obtained for PS3 and PS4.

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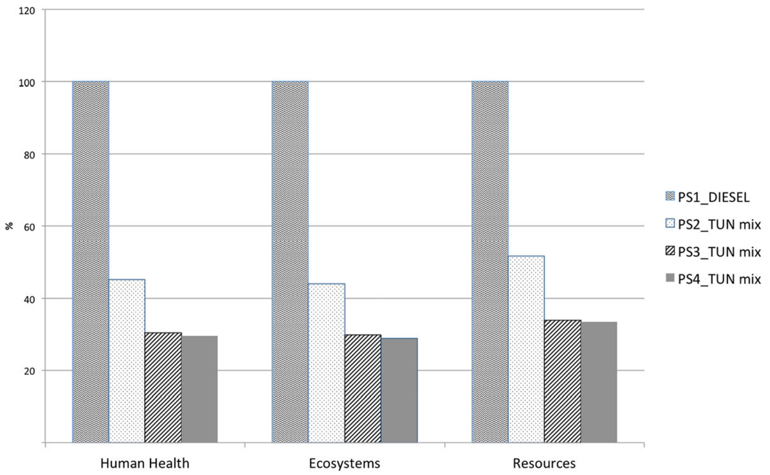

Figure 4. Endpoint LCA results for the pumping of one cubic meter in PS1 to 4 for the baseline situation (Tunisian electric mix, depth 35 m), powered either with diesel or with the Tunisian electricity mix, Recipe 1.07 (H). This figure is available in colour online at wileyonlinelibrary.com/journal/ird

Contribution of the different pumping system components to environmental impacts

Contribution analysis was performed to identify the main contributors to each impact category but also to identify the room for—environmentally friendly—improvements. As seen above, in all four systems the impacts are predominately due to energy consumption. PS2 is the system for which the impact from pump building appears best, because of the limited lifetime of the pump. Therefore, it is chosen to illustrate contributions. Figure 5 displays the contribution to midpoint impacts of each of the three pump components: namely the infrastructure (open well and tubewell), the pump and the power source.

Impacts are dominated by the energy required for operating pumps, nevertheless the impacts linked to materials and energy involved in pump manufacturing, as well as well or borehole drilling/construction, are significant. Pump impacts reach 90% for metal depletion and 60% for human toxicity, freshwater ecotoxicity and eutrophication and agricultural land occupation, due to its composition.

For climate change, the infrastructure and the pump barely contribute more than 6%. This is in line with other studies (Tyson *et al.*, 2012).

The contributions of each component of the pumping system to the three endpoint impacts are shown in Figure 6. Endpoint results are also overwhelmingly driven by energy impacts, reaching up to 95%. When investigating further, we note that 86% of damage to human health and 96% of that to ecosystems are due to the midpoint impact, i.e. 'climate change'. Furthermore, fossil depletion is virtually the only contributor to 'resource depletion' damage. For this last damage, the high

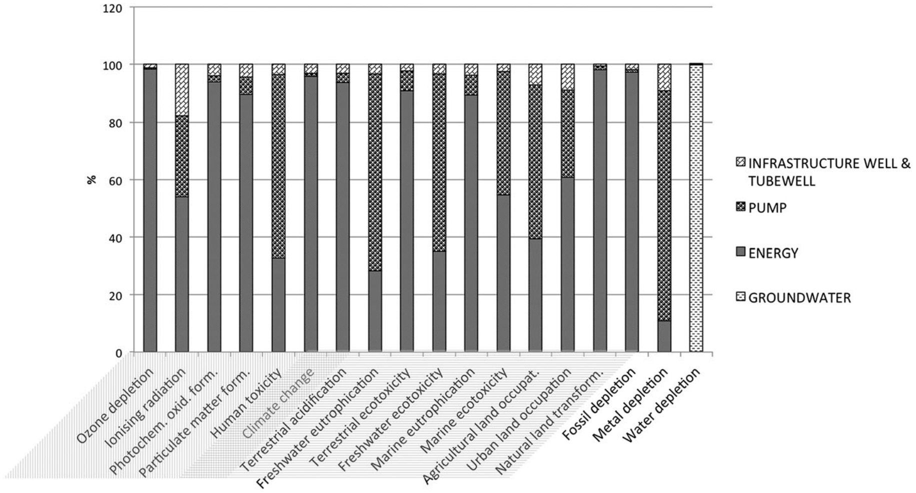

Figure 5. Contribution analysis of Midpoint impact categories of the pumping system components. The PS2 example electricity powered water pump, Tunisian electricity mix. Total dynamic head= 64 m, Recipe 1.07 (H)

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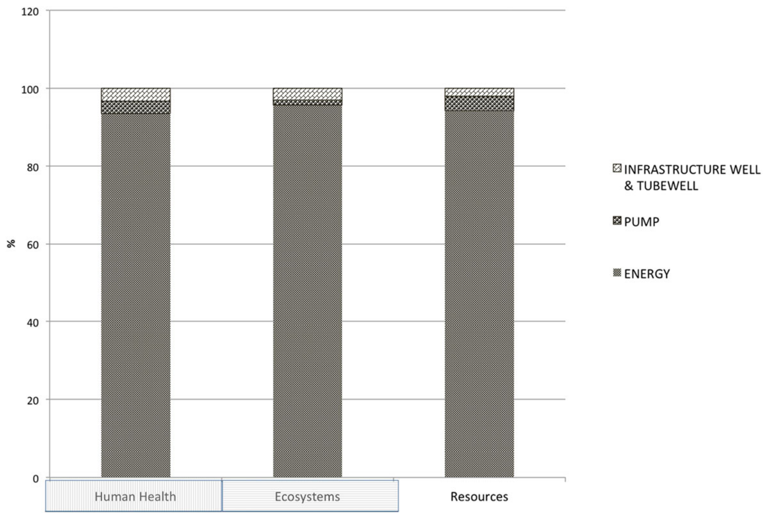

Figure 6. Contribution analysis to endpoint impact categories of the pumping system components. PS2 example: electricity powered water pump, Tunisian electricity mix. Total dynamic head= 64 m, Recipe 1.07 (H). This figure is available in colour online at wileyonlinelibrary.com/journal/ird

significance of energy is also due to the fact that Recipe does not take into account water depletion. Other methods, as will be shown later, include water depletion in resource damage.

The nature of the power source in itself, which is coal-based, is very harmful, both to human health and the environment, as well as to resource depletion. If electricity were provided by wind power, the power source contribution to damage, and to the midpoint impact of climate change, would be limited to one-third of the total.

Apart from the nature of the power source, the important groundwater table depth, 35 m, and the consequently high energy required for pumping, may mask the infrastructure and equipment contributions. Consequently, we will test the sensitivity of the contribution analysis to a lesser groundwater table depth.

Analysis of sensitivity to the total dynamic head

For a scenario of a total dynamic head set at 14 m, i.e. the groundwater table depth set at 5 m and surface irrigation, energy requirements decrease, but are still responsible for 75% of all damage (versus 95% when TDH =64 m). The pump is likely to contribute to resource depletion, the infrastructure to ecosystem damage, and both contribute equally to human health impacts. Lifetime may be extended due to the reduced flow pressure required but this has a negligible impact on results. These findings have already been pointed out in the section ’Comparison of LCA results/environmental impacts of contrasted water pumping systems’.

The major, if not overwhelming, contribution of energy to both midpoint- and endpoint-level impacts underlines the need to focus efforts on developing power sources emitting less greenhouse gases and on more energy-efficient pumping systems.

Indeed, all power sources do not have the same impact. Consequently, we have carried out a sensitivity analysis of pump efficiency and power sources.

Analysis of sensitivity to the power source

The midpoint impacts of using 1 MJ of different power sources are displayed in Figure 7 for diesel, electricity from Tunisia, the EU 27 electricity mix, electricity obtained from coal-burning and a photovoltaic mix. The photovoltaic mix emits the least greenhouse gases, around five times less than diesel which is the second least impacting power source on climate change. This photovoltaic mix performs averagely well, except on: toxicity, ecotoxicity and mostly on metal depletion. On terrestrial ecotoxicity, the photovoltaic mix is three times more impacting than diesel, and on metal depletion, this mix is five times more impacting than electricity generated from coal.

Electricity from coal is the most impacting power source for almost all impacts, except for ozone depletion, ionizing radiation, natural land transformation and metal depletion. Ionizing radiation impacts are 10 times greater for the EU mix than for electricity generated from coal, as the former includes a 27% nuclear power share.

Endpoint-aggregated results show: the photovoltaic mix is the least impacting in each of the three areas of protection, followed by diesel combustion. Then in intermediate position come the EU 27 mix and the Tunisian mix, having similar impacts. The most impacting power source is electricity generated from coal-burning.

Thereafter, these four different electricity generation mixes and diesel power are applied to pumping contexts, either PS1 (for diesel) or PS2 (for electricity). Figure 8

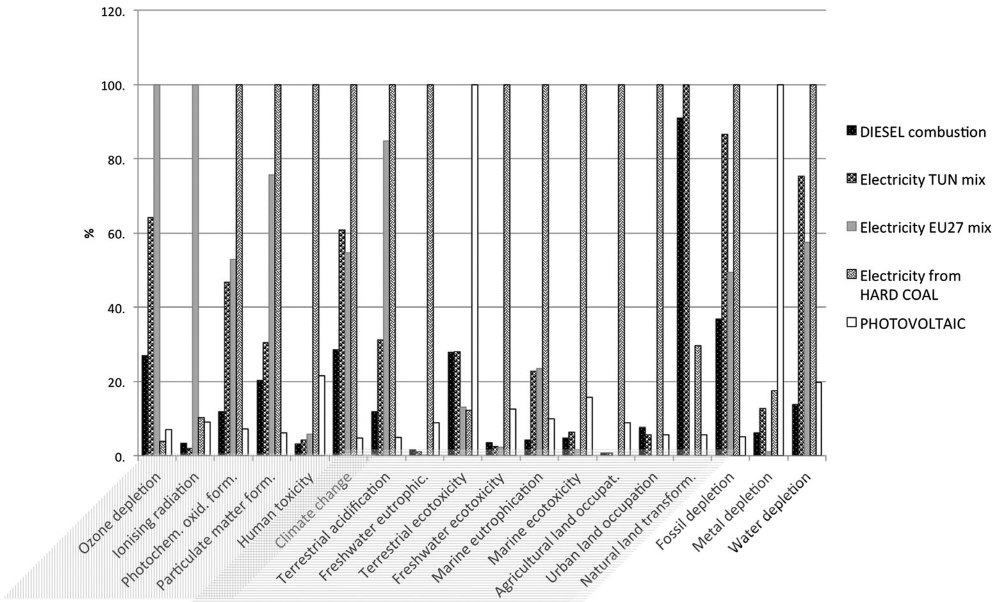

Figure 7. Midpoint impacts resulting from the use of 1 MJ from different power sources, Recipe 1.07 (H)

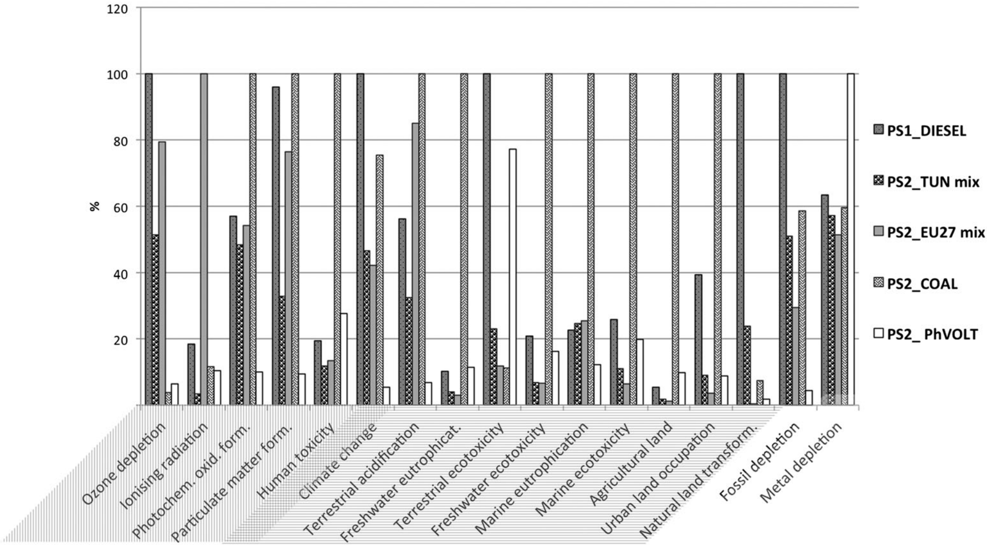

Figure 8. Midpoint impacts for the pumping of 1 m3 with PS1 (diesel) and PS2, the latter being powered by electricity generated from: coal-burning, the EU27 mix, the Tunisian mix, or photovoltaic, Recipe 1.07 (H)

displays the LCA results of PS1 powered by diesel, versus PS2, powered by electricity from coal, the EU 27, the Tunisian mix and the photovoltaic mix.

The hierarchy between PS1 and PS2 powered by the Tunisian electricity mix has already been studied in the baseline situation, as illustrated in Figure 3. The ranking between PS2 powered alternately by each of the four electricity mixes cited above is similar to the ranking obtained for power sources, displayed in Figure 7. Whereas PS1 was undoubtedly worse than PS2 in the baseline study, where electricity was mostly generated from natural gas, results are significantly different when the electricity mix changes. Indeed, in Figure 8, PS2 powered by electricity from coal is the worst for 10 out of 17 impact categories. Thus, an electric pumping system, when powered by a 'bad' electricity mix, i.e. with regard to its impacts on the environment, as with coal, could be as impacting as a diesel-fuelled pumping system.

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PS1 powered by diesel remains the worst system for climate change, ozone depletion, terrestrial ecotoxicity, natural land transformation and fossil depletion. Given the major share of climate change in the aggregated categories of human health and ecosystems, it is not surprising that PS1 is the most impacting at endpoint level (Figure 9).

Impacts generated by the diesel-powered pump are only twice those obtained for pumps powered by Tunisian electricity. By contrast, the global efficiency of pumping systems powered by diesel is five times less than those powered by electricity (Table II). In fact, the performance gap between the two systems is balanced because 1 MJ of diesel pollutes on average less than all other electric mixes assessed in this study, except the photovoltaic one.

Our results have also been compared to Tyson *et al.*'s (2012). These authors showed that a diesel-powered water pump emitted less greenhouse gases than an electricity-powered submersible pump, coal being the major electricity feedstock. These results are not in line with our findings. The possible explanation for this discrepancy is the value of the global pump efficiency of PS1. It is set at 28% in Tyson *et al.* (2012) and has been calculated at 8% in our study. Pump efficiency is a major driver of energy consumption (Jackson *et al.*, 2011), and consequently of greenhouse gases. Moreover other impacts will differ depending on the type of power source used.

This tends to confirm the critical influence of pump efficiency on impact results. In line with this argument, an analysis of sensitivity to pump efficiency has been performed.

Sensitivity to both power source and diesel pump efficiency

Table V compares environmental performance of the four pumping systems (PS1–PS4) based on combinations of various efficiency levels (of PS1 fuelled by diesel) and power sources. Three patterns are identified:

1. In the dark grey boxes, i.e. in 8 out of 12 cases, PS1 is the most harmful system. It corresponds consistently with either the photovoltaic electricity mix whatever the efficiency, or the lowest values of efficiency (i.e. 8% and partly 16%);
2. In the white box, PS1 is the least harmful to the three areas of protection, and thus to climate change, in accordance with Tyson *et al.* (2012); this corresponds to its highest efficiency levels (i.e. 28%) and to electricity generated from coal-burning.
3. In the light grey boxes, PS1 performs averagely well. It is virtually always better than PS2 and equivalent to PS3 and PS4 for human health.

In case electricity is generated from coal, PS1 becomes less harmful than PS2 as soon as the efficiency reaches 16% (3). This is due to the very polluting nature of this electricity mix. The same reason explains why at the 28% efficiency level, PS1 becomes even better than the very efficient PS3 and PS4 pumping systems. This only holds for electricity from coal.

When comparing PS1 and PS2, the systems are alternatively less or more impacting according to the electricity mix for the same pump efficiency. This is despite the fact that their infrastructures are similar and equipped with surface water pumps. These results make us very reluctant to put forward generic rules for the ranking of pumping systems with regard to their environmental impacts. Contribution analysis displayed in Figure 5 illustrates the significant role of energy in these energy-intensive systems. Findings emphasize the need to address pumping system

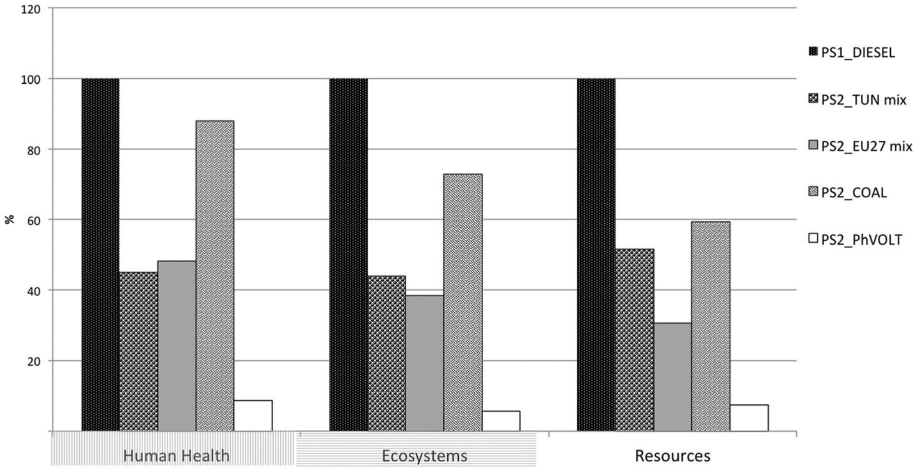

Figure 9. Endpoint impacts from pumping one cubic meter with: PS1 powered by diesel, PS2_TUN mix powered by the Tunisian mix, PS2_EU27 mix powered by the EU 27 mix, PS2_COAL powered by electricity from hard coal, PS2_PhVOLT powered by photovoltaic mix respectively, Recipe 1.07 (H)

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Table V. Endpoint impact ranking of the different pumping systems

	Diesel-powered pump global efficiency		
Electricity mix	8%	16%	28%
Photovoltaic mix	HH-E-R 4 ≈3 ≈2 <1	HH-E-R 4 ≈3 ≈2 <1	HH-E-R 4 ≈3 ≈2 <1
Tunisian mix	HH-E-R 4 ≈3 <2 <1	HH: 3 ≈4 <2 <1 E: 3 ≈4 <2 <1 R: 3 ≈4 <2 ≈1	HH-E-R: 1 ≈3 ≈4 <2
EU 27 mix	HH-E-R 4 ≈3 <2 <1	HH: 3 ≈4 <2 ≈1 E-R: 3 ≈4 <2 <1	HH: 1 ≈3 ≈4 <2 E: 3 ≈4 <1 <2 R: 3 ≈4 <1 ≈2
Electricity from coal	HH-E-R 4 ≈3 <2 <1	HH-E: 1≈ 3 ≈4 <2 R: 4 ≈3 <1 <2	HH-E-R: 1 <4 ≈3 <2

PS1 to PS4, « 1 » means « PS1 ») for various types of electricity mixes and values of overall diesel pump efficiency; HH, E and R stand for human health, ecosystem and resources respectively; A < B means A is less impacting than B, A ≈ B means both are similar.

sustainability by considering the specific mix of national power sources and local pumping system efficiencies.

In our case study, the very poor efficiency of PS1 is due to poor pump quality and poor maintenance. Furthermore, the reasons for this situation are: the narrow range of commercial offers for pumps, the limited investment capabilities of farmers and finally the low level, or total absence, of technical support regarding pumping system management and maintenance.

This sensitivity analysis demonstrates that caution must be exercised when ranking pumping systems according to their environmental impacts. Up to now, decision-making regarding pump choice has been driven by energy efficiency (Jackson *et al.*, 2011). This study confirms that although energy efficiency is an important factor, taken alone it is not sufficient to satisfactorily describe the environmental footprint of a system.

Achieving a better understanding of the food–water–energy nexus with LCA

In this paper, we have focused on the environmental impacts brought about by the extraction of 1 m^3 of water at 2 bars from a 35 m-deep groundwater table. We saw that the 'water depletion' impact category was not a discriminating criterion, because the amount of water extracted, on which this category is based, was always the same whatever the pumping system.

If we no longer consider the extraction of water but the production of crops thanks to irrigation, the amount of water used per kilogram of product will vary according to the crop, the climate, the soil, the efficiency of the whole irrigation system. By doing so, we converge towards the issue of the food–water–energy nexus, which has been cited in the literature. In this case, the water depletion category must be taken into account when attempting to model damage caused at endpoint level. This is not taken into consideration in the Recipe endpoint. Here we propose to look at the damage caused by water depletion by applying the methodological framework of Pfister *et al.* (2009) within Recipe, LCIA endpoint method (Figure 10).

This method models potential damage arising from water consumption. These negative impacts are then weighted using a water stress index. The latter, which attains a maximal value in our semi-arid to arid context, is modelled at country or watershed scales. We use Pfister's framework to perform the LCA for the pumping of 1 m^3 in PS2 and assume that 100% of water pumped is consumed. In addition to the impacts displayed in Figure 6, more significant damage to resources is obtained when 'groundwater depletion' is accounted for by this framework. Given the local conditions, we have estimated extra damage to resources at 1900%. In other conditions, additional damage may be caused to human health and to the ecosystems as well. The damage to resources is quantified in dollar terms, based on the 'backup technology concept', i.e. the monetary quantification of energy required to restore the amount of groundwater depleted by operating a desalination plant as the backup technology (Stewart and Weidema, 2005). 'Groundwater depletion' is therefore a crucial issue that should be taken into account when attempting to characterize the food–water–energy nexus as a whole. In our case, i.e. groundwater table depth set at 35 m, environmental impacts arising from water depletion are far greater than those

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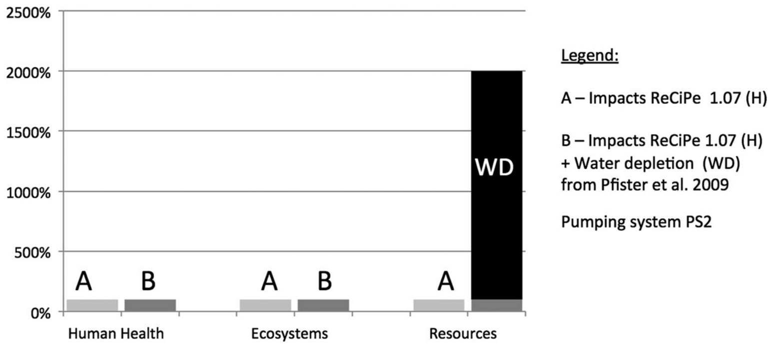

Figure 10. Comparison of damage assessment of PS2 using ReCiPe 1.07 (H) (Goedkoop and Huijbregts, 2012) method versus ReCiPe 1.07 (H) +water depletion from Pfister *et al*. 2009

related to energy use, within Pfister's framework and considering its limitations. The water–energy nexus is overwhelmingly dominated by water depletion and it would be interesting to model the groundwater table depth for which the nexus would be at equilibrium. In addition to damage caused to resources, extra damage could occur to ecosystems, in the case irrigated areas are surface water fed or groundwater fed from shallow groundwater tables.

CONCLUSION

The objectives of this paper were: to assess the potential environmental impacts of different pumping systems, and to evaluate the relative contribution to impacts of infrastructure, pump and power source, by performing an LCA. The contribution analysis confirmed the importance of greenhouse-gas-emitting fossil energy to midpoint impacts and their overwhelming contribution to damageat the endpoint level, strengthening the viewpoint of Jackson *et al.* (2011) and Tyson *et al.* (2012). Indeed, as this type of system is very energy-intensive, the energy used is almost the only contributor to damage, namely to human health, the ecosystem and resource depletion. The first two damage categories—human health and ecosystem quality—are driven by climate change and the latter—resources—by fossil depletion. Water depletion is usually not accounted for in damage assessment. But we have shown that damage to resources increased by a factor of almost 20 when water depletion was accounted for, by using the spatialized framework of Pfister *et al*. (2009).

Nevertheless, within LCA methods routinely run in LCA software until now, such as Recipe, our work confirms that energy is the main issue.

We have also demonstrated that pump efficiency was not the only parameter that should be considered when ranking pumping systems. The power source must also be taken into account in order to perform an accurate environmental assessment. Indeed, the diesel-powered pumping system is the least environment-friendly system when electricity is provided by natural gas and diesel powered pump efficiency is less than 16%. However, the diesel powered pumping system happens to be the most environment-friendly when electricity is provided by coal and diesel-powered pump efficiency is equal to or greater than 28%. Aggregated LCA results at endpoint level showed how different the ranking can be if different power sources and pump efficiency levels are considered. The pumping system's environmental 'footprint' has therefore to be studied in a given energy context.

This study represents a step towards designating more environment-friendly pumping systems thanks to the holistic methodological framework of LCA which is used here to broaden the range of impacts assessed. In fact, simply focusing on greenhouse gases and energy will be increasingly irrelevant as we move towards non-fossil energies.

In addition, addressing the food–water–energy nexus through the LCA framework is highly context-specific and would benefit from ongoing methodological developments about the quantification of environmental impacts due to water depletion. The next step will be to apply LCA to the production of different crops, while taking into account the environmental footprint of water pumping and irrigation.

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