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Development of WEF-P Nexus based on product-supply chain: A case study of phosphorous fertilizer industry in Morocco

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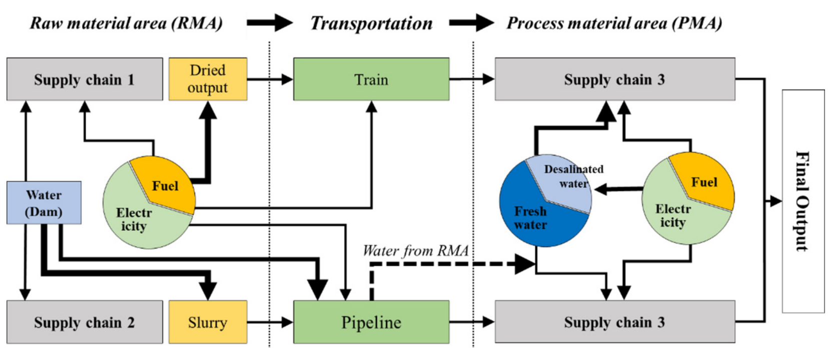
HIGHLIGHTS

- The WEF-P nexus based on product and supply chain was developed.
- The WEF-P nexus quantified impacts of changes in supply chain on water-energy balance.
- The WEF-P nexus showed the different impacts on resource management in raw and final products areas.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study was to analyze various sustainability strategies for phosphate and phosphorous fertilizer production systems from the perspective of their holistic impacts on water, energy, and CO_2 emissions. The study was conducted using the Water-Energy-Food (WEF) Nexus Tool 2.0, adapted to include the phosphate industry (WEF-P tool). It assesses the scenarios based on priorities identified by the Moroccan phosphate industry, such as the environmental impact of transporting phosphate rock by train and phosphate slurry by pipeline and increased desalinated water use. Results show that each scenario's sustainability can be assessed in terms of phosphate production, processes, resource (water and energy) availability, and CO_2 emissions in mining and manufacturing areas. The analytical methodology of the tool is based on an integrated supply chain and life cycle assessment, which includes the production flows linking mining phosphate and manufacturing phosphorous fertilizers and their water and energy supply systems. Field surveys were used to identify the supply chain and estimate the relationships between production and resource consumption in each process. The tool is a decision-support platform that produces sustainability indices for multiple scenarios of resource allocation (water and energy) and CO_2 emissions, allowing stakeholders to compare potential outcomes and formulate decisions based on their understanding of the actual trade-offs involved.

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Nomenclature

CFP_E (tons/MWh) CO_2 footprint generated by electricity
DCO_2 (tons) Direct CO_2 emissions
$EC_{desalination}$ (MWh or gallon) Energy consumption of desalination plants in manufacturing areas
$EC_{manufacturing\ area}$ (MWh or gallon) Total energy consumption in the manufacturing area
$EC_{mining\ area}$ (MWh or gallon) Total energy consumption in the mining area
$EC_{pipeline\ station}$ (MWh or gallon) Energy consumption in the pipeline station
$EC_{pipeline\ terminal}$ (MWh or gallon) Energy consumption at the pipeline terminal station
EC_{train} (MWh or gallon) Energy consumption by train
$EFP_{desalination}$ (MWh or gallon/ton) Energy footprint of desalination
EFP_i (MWh or gallon/ton) Energy footprint
$EFP_{pipeline\ station}$ (MWh or gallon/ton) Energy footprints in the pipeline station
$EFP_{pipeline\ terminal}$ (MWh or gallon/ton) Energy footprint of the terminal station
EFP_{train} (MWh or gallon/ton) Energy footprints in transportation by train
$ELC_{manufacturing\ area}$ (MWh) Total electricity consumption in the manufacturing area
$ELG_{power\ plant}$ (MWh) Electricity generation in power plants using high-pressure and medium-pressure steam
ELS_{ONEE} (MWh) Electricity supplied from ONEE
$InDCO_2$ (tons) Indirect CO_2 emissions
P_i (tons) Production
$P_{phosphate\ rock}$ (tons) Production of phosphate rock
P_{slurry} (tons) Production of slurry
$WC_{manufacturing\ area}$ (m^3) Total water consumption in the manufacturing area
$WC_{mining\ area}$ (m^3) Total water consumption in the mining area
$WC_{pipeline\ station}$ (m^3) Water consumption in the pipeline station
WFP_i (m^3/ton) Water footprint
$WFP_{pipeline\ station}$ (m^3/ton) Water footprint at the pipeline station
$WG_{desalination}$ (m^3) Volume of desalinated water in the manufacturing area
WS_{ONEE} (m^3) Volume of water supplied from ONEE
$WT_{pipeline}$ (m^3) Volume of water transported from the mining area to the manufacturing area by pipelines
$WT_{tranportation}$ (m^3) Total volume of water transported from mining to manufacturing area by pipeline
W_{slurry} (m^3) Volume of embedded water in the slurry
i The process for the final product fertilizer
CFF_F (tons/gallon) CO_2 footprint of the burning fuel
ELC (MWh) Electricity consumption
FC (tons/gallon) Fuel consumption by the machine excluding fuel use for electricity generation
j type of fertilizer

1. Introduction

With over 75 % of global phosphate reserves, Morocco is a key player in the international phosphate market. Morocco produces 30 % of the world's marketed raw phosphate and related products and is one of the world's largest producers of fertilizers (OCP, 2013). Its phosphate industry accounted for 30 % of the country's gross domestic product and nearly 20 % of the value of its national exports over the 20th century (Croset, 2012). The aim of Morocco's industrial development program was to double the current mining capacity and triple the chemical production capacity by 2020. This increased production promises to become a major source of income for Morocco and boost crop yields in a matter that helps address global food security.

Nevertheless, phosphate mining and its chemical processing require considerable energy and water and are responsible for substantial CO_2 emissions. The water-intensive processes used in phosphate production and pumping or desalinating water also carry energy tags; however, desalination relieves Morocco's scarce freshwater supplies while securing the quantity of water needed to process phosphate. In particular, fossil fuels produce nearly 90 % of Morocco's electricity (IEA, 2014), giving energy consumption in Morocco a high CO_2 emissions tag. Phosphate production involves intricate processes that consume multiple resources. Changes in the production system, such as switching the mode of transport of raw products or adding new manufacturing processes, can and usually impacts resource consumption. Thus, throughout the entire mining to the manufacturing process, it is necessary to consider the trade-offs involved in the use of resources and production of final goods through a decision support system that provides a quantifiable trade-off analysis of decisions, such as water allocation, an increase of production, and mode of transport.

Water-Energy-Food (WEF) Nexus framework could be suggested as offering a holistic, transdisciplinary, multi-stakeholder, inclusive platform for determining the trade-offs associated with resource allocation (Mohtar and Daher, 2014; Mohtar and Daher, 2016). The nexus was identified during the 2008 annual meeting of the World Economic Forum; nexus thinking emerged from the understanding that natural resources are becoming limited (Hoff, 2011). The WEF Nexus was identified as a Global Risk in 2011 (WEF, 2011). Policy and research communities worldwide have called for action to develop strategies to provide a comprehensive nexus approach (Bhaduri et al., 2015). As a result, various studies have been conducted to understand that natural resources are significantly limited by economic growth and the goals associated with societal well-being through the nexus concept (Biggs et al., 2015; Hoff, 2011; Ringler et al., 2013). The potential benefits of a more holistic policy and regulatory design based on the nexus concept include increased economic and resource efficiencies and improved livelihoods.

The nexus approach provides a tool from which it is possible to quantitatively assess the trade-offs in the decisions to increase production, change processing, and allocate specific resources or combinations of resources. In particular, the Sustainable Development Goals (SDGs) emphasize the need to consider the connections between various resources to achieve sustainable production and consumption. Research is being conducted to minimize the water and energy used during food production, while ensuring food security. Also, some studies examine energy requirements in supplying water while looking at water requirements in energy production at the same time. In such studies, the concept of Nexus is widely being adopted because sustainable resource management should consider all resources required during the overall process of production and transport of final products, rather than only looking at the use or the amount of the final product. The Nexus highlights the interconnections between water, energy, and food resources. It is utilized in the analysis of trade-offs and synergies between different resources that occur when a specific resource is managed. There are many case studies where food is considered as the final product, and the Nexus concept is used to analyze the water and energy consumption during food production. Recently, the water resource used during food production and trade is also included in the Nexus through the concept of virtual water. This allows investigation of water resource dependencies among different regions that are geographically far apart but connected by food trade.

However, there is no standardized methodology for analysis involving the energy-water-food nexus but the life cycle assessment (LCA) methodology has been used for quantifying the resource consumptions and environmental impacts throughout the life cycle. Interest in sustainability has increased (Hoogmartens et al., 2014) resulting in LCA incorporating into various fields to assess the sustainability of thematic strategies (Lundin and Morrison, 2002; EU Commission, 2005; De Benedetto and Klemeš, 2009; Heijungs et al., 2010; Guinee et al., 2010). Research on Nexus using LCA has been categorized into three groups: presentation of concepts and frameworks, application and case studies, and review papers. For example, Karabulut et al. (2018) proposed a synthesis matrix system that describes the relationship between the use of natural resources for food, energy, and ecosystems along the concept of ecosystem-water-food-land-energy nexus, emphasizing the importance of a holistic approach within LCA. Wang and Chen (2019) built the framework to assess the environmental impact of energy-water nexus competing with each other to investigate the energy, water, and carbon footprint based on 3 scope hybrid life cycle analysis. Laurentiis et al. (2016) discussed how LCA method might be applicable for energy, water, and food nexus approach to achieve food security, taking into account the interactions between resources, and synergies and trade-offs that arise from the way they are managed. In terms of application and case studies, Chen et al. (2020) analyzed resource flow of WEF nexus (tap water supply, oil refining, electricity generation, thermoelectric power plants, irrigation, animal husbandry, and aquaculture) and associated environmental impacts using LCA in Taiwan. Armengot et al. (2021) evaluated the food-energy-water nexus (FEWn) of four cacao production system scenarios: two full-sun monocultures and two agroforestry systems under conventional and organic management, through LCA and water footprint concept. Pacetti et al. (2015) analyzed the production of biogas from the anaerobic digestion of energy crops under different scenarios of geographical locations and crops as a case study of the multiple interconnections between water, energy, and food elements. In particular, the trade-offs between water use and bioenergy production have been investigated through the integration of water footprint and LCA methodologies. Pradeleix et al. (2015) assessed the environmental impacts and relationship between water and energy of contrasted groundwater pumping systems, using LCA in semi-arid central Tunisia. Muiruri et al. (2022) applied the nexus between end-of-life strategies and LCA to the production and uses of PHAs (polyhydroxyalkanoates) to understand its environmental impacts. Zhang et al. (2021) proposed an optimal modeling approach for generating efficient agricultural water and land management alternatives and reducing carbon emission in agricultural water-energy-food nexus system, using a novel approach consisting of carbon footprint LCA method. In a case study with a broader scale, Egilmez and Park (2015) traced the life cycle impact of the US transportation and manufacturing sectors' nexus considering relationships of direct (onsite) and indirect (supply chain) industries. Yuan et al. (2018) proposed an environmental impact minimization model, which considers the WEF nexus and LCA to analyze appropriate bioenergy production rates while comparing the benefits of bioenergy with the current renewable energy policy in Taiwan. Li et al. (2012) evaluated the nexus between water consumption, energy production and CO2 emissions of wind power, adopting input-output based hybrid life cycle analysis in China. Li and Ma (2020) highlighted that environmental impacts derive from not only direct resource consumption but also preparation and production for resource generation (indirect consumption), focusing on the effects of direct and indirect resource consumption with a life-cycle approach. As review papers, Mannan et al. (2018) reviewed the interlinkages inherent in the water-energy-food nexus to develop suitable quantification methods, and concluded that an integrated analysis using LCA and energy-water-food nexus methodology is necessary to determine environmental impacts for different scenarios, essentially influencing energy-water-food resource sectors. Batlle-Bayer et al. (2020) reviewed studies that analyzed the effect of diet transition scenarios on GHG emissions, land use, and water footprint, comprehensively considering the approach using Water-Energy-Food nexus and LCA methods. Also, they suggested that LCA is particularly important for understanding the interconnections in the nexus approach. Many researchers reviewed literature to understand the current status of the water–energy–food nexus, focusing on its methodology, and the process through which the nexus approach has been academically and geographically expanded and synthesized. LCA is applied as one of the methods to quantify the entire process of resources and environmental impacts for production (Endo et al., 2020; Corona-Lopez et al., 2021).

In the Nexus approach, the interconnections between products, water, and energy in each process during the production, from the processing of raw materials to the production of final products, could be analyzed within the supply chain. In addition, it could be shown that geographically separated regions that have no direct exchange of water and energy can still be connected in their Nexus systems through transport of products. Specifically, change in the mode of transport could result in excessive water consumption in one region, while water and energy were saved in another region. Accordingly, the boundary of resource management can thus be expanded across regions. The sustainable production, which is emphasized in SDG, requires a more holistic approach of considering supply chains in all regions where products are transported, rather than focusing only on individual region of production. Therefore, the aim of this study was to develop a phosphate (WEF-P) tool that holistically assesses the sustainability of possible management strategies in the production chain defined by the Khouribga mining area–Jorf Lasfar manufacturing area in Morocco. This tool quantitatively identifies the interactions between supply chain components and implicitly acknowledges the mutually dependent relationship between phosphate production and resource management. Specifically, the study:

1. Analyzes the integrated supply chain and water-energy footprints from mining to manufacturing areas;
2. Analyzes water and energy use and carbon emissions in the supply chain;
3. Evaluates the sustainability of potential scenarios through a trade-off analysis.

2. Method

2.1. Overall framework of the WEF-P tool

The WEF-P tool was based on the framework of WEF Nexus Tool 2.0, developed by Daher and Mohtar (2015), and it is specialized for the phosphate industry to address strategic decisions, such as the mode of production or changes in the mode of transport of raw materials. The tool's scope was developed to consider the phosphate production lines from the mining area (Khouribga) to the manufacturing area (Jorf Lasfar). In other words, raw phosphate, which is the main output in Khouribga, is transported by trains or pipelines to Jorf Lasfar, as illustrated in Fig. 1. The Khouribga mining area includes three primary mining sites: the Sidi Chennane (SC), Merah Lahrach (MEA), and Bani Amir (BA), whose outputs are raw phosphate (rock and slurry) that is subsequently transported, either by train or pipeline, to the Jorf Lasfar manufacturing area, in which six producers of fertilizers and phosphoric acid are located: Maroc Phosphate (MP).

The goal and scope of the WEF-P tool provide the direction of the scenarios and are related to increased production, less resource consumption, and high sustainability. An overall framework of the WEF-P tool was built, consisting of scenarios, supply chain analysis, and resource quantification, as summarized in Fig. 2. Users can create relevant scenarios that are quantified to produce their resource footprints throughout the supply chain. Scenario sustainability is assessed by analyzing the trade-offs of environmental impacts, including water and energy availability and CO_2 emissions.

In particular, the element of food in the Nexus system was replaced with a specific 'product' in the WEF-P tool. In addition, water and energy consumption during the manufacturing process of the product was analyzed, from processing of raw materials to the production of final product output. Changes in the water-energy balance with any changes in the supply chain were also investigated. Specifically, we looked at how transport of materials between geographically separated regions can change the regional supply chains and their production-water-energy nexus.

The WEF-P tool also considers the transportation of raw and final products. For example, changing the mode of transport is one of the technical adaptations in the production process that affects final product's water, energy, and CO_2 emission footprints. Transportation by train requires drying of raw phosphate, a process that consumes energy. Transport by pipeline requires adding water to the raw phosphate to produce a slurry; however, this process

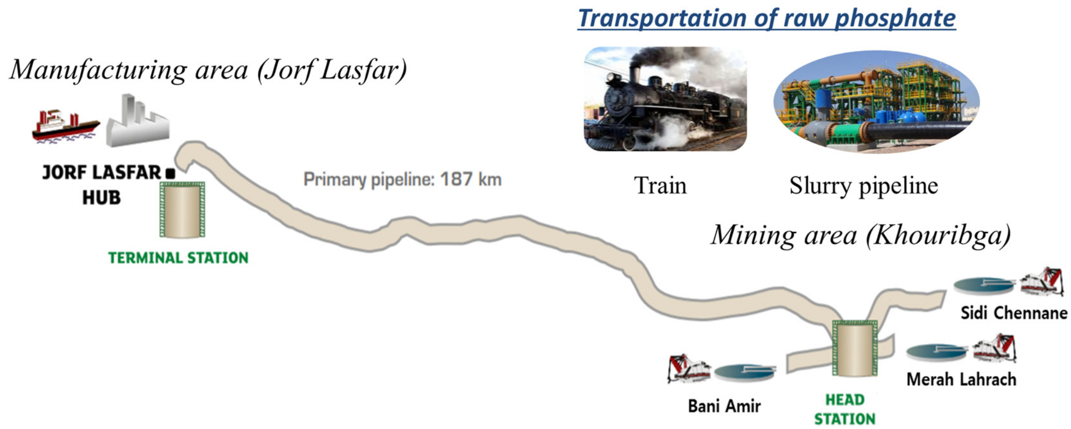

Fig. 1. Study area, including the phosphate mining area (Khouribga), the fertilizer manufacturing area (Jorf Lasfar), and the pipeline system.

uses less energy and consumes larger quantities of freshwater. The transport question offers an example of resource interlinkages that affect allocation decisions based on the relative trade-offs of production process decisions. It also offers an example of intersectoral trade-offs: the pipeline system transports surface water from mining to the manufacturing area, which provides additional water resources to the manufacturing area.

2.2. Development of the WEF-P tool based on the integrated supply chains and life cycle assessment

2.2.1. Integrated supply chains of products based on transportation systems

To analyze the trade-offs of the strategies relating to production and transportation in the phosphate industry, we first need to quantify water and energy consumption; however, production lines and water-energy supply processes are complicated. For example, WEF-P includes processes of products from raw materials (phosphate rock) to final products (phosphorous fertilizers) in addition to water and energy supply systems such as desalination plants. Therefore, the WEF-P tool relies on identifying supply chain processes that produce the final products. A *supply chain* is defined as a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, or information from source to the customer (La Londe and Masters, 1994; Mentzer et al., 2001); in manufacturing a product, it can involve several independent entities before it is placed in the hands of end-users. The supply chain in this study integrates the raw materials from the mining area and the final products from the manufacturing area based on transportation systems, such as trains and pipelines, as shown in Fig. 3. The amount of raw phosphate transported from the mining area to the manufacturing area depends on the amount of final products (phosphorous fertilizers), and the output in each process in the mining area depends on the type of phosphates, such as phosphate rock and slurry. In this study, tons of phosphate products indicate the commercial metric tons (TSM) in all processes and transportation systems that will later be processed into exportable products at the industrial site. In other words, phosphorus material contained in phosphate rocks was considered as a functional unit. Even after washing and drying of rocks, the amount of phosphorus material does not change, and the same amount is contained in the final product of phosphorus fertilizer. The actual amount of phosphorus material per unit of phosphorus fertilizer produced is a classified information and could not be disclosed. However, the water and energy consumption in all production processes was estimated based on the amount of phosphorus materials.

The supply chain in the mining area focuses on the quality of the phosphate rock and the choice of the transportation system (train or pipeline), which determine the processes used in the subsequent supply chain. For example, in Khouribga, phosphate is transported either by train (dry aggregates) or slurry pipeline to the main fertilizer manufacturing site. The two transportation systems have distinct processes: the pipeline supply chain includes washing (water) and adaptation processes that produce a slurry, and the train supply chain includes the fuel-intensive drying process. It is possible to quantify the flow of products according to the transportation

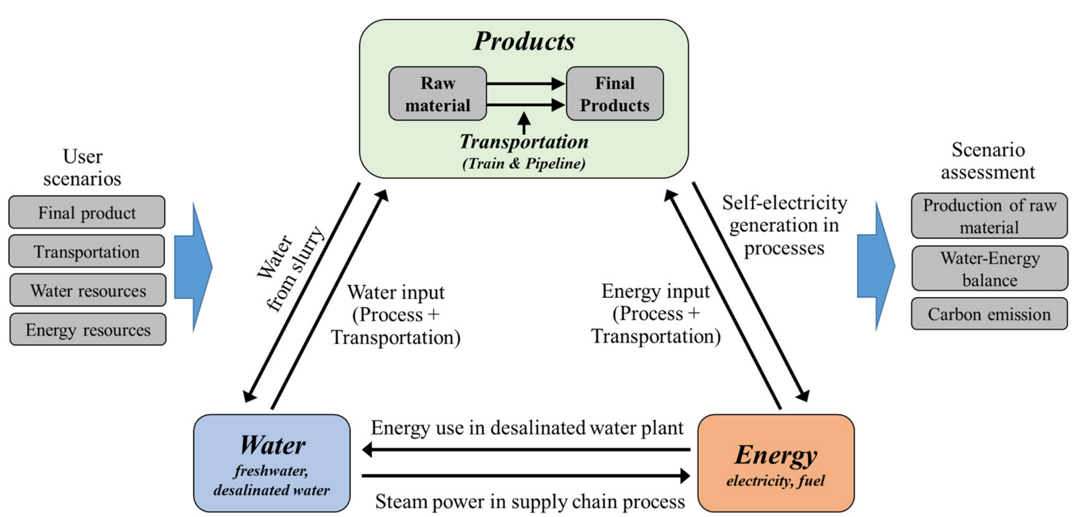

Fig. 2. Overall framework of WEF-P tool.

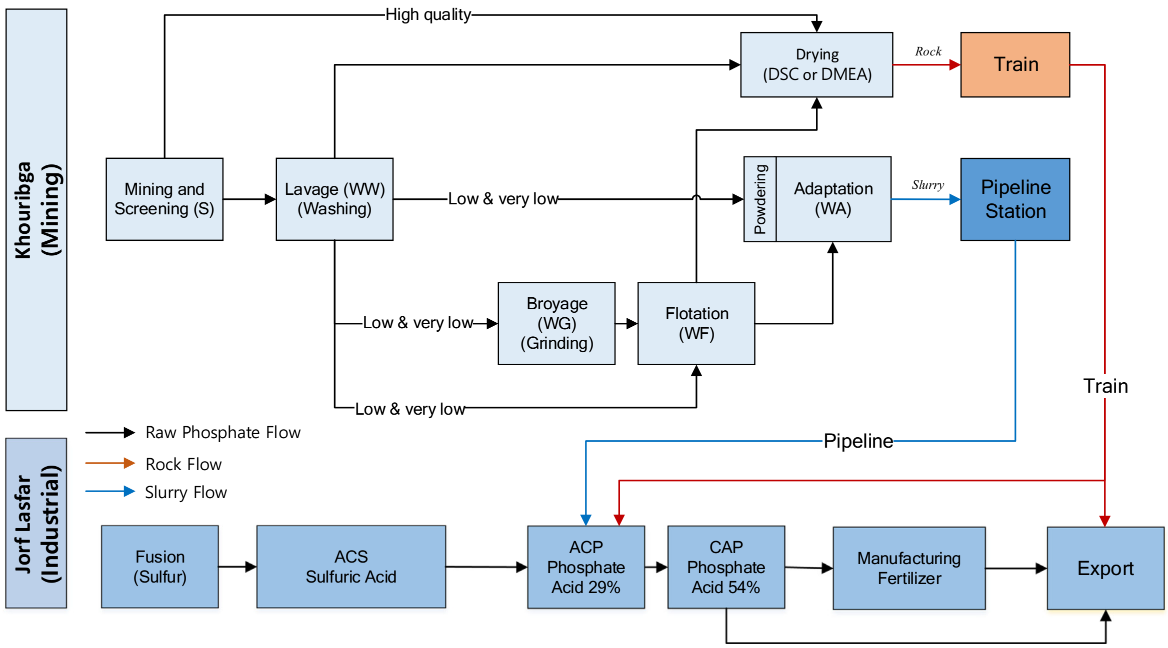

Fig. 3. The functional processes and product flow between mining and industrial areas.

system used: when transportation is changed from train to pipeline, supply lines also change, and the adaptation process replaces the drying process. High-quality phosphate rocks transported by trains undergo mining, screening, and drying. Low- and very-low-quality phosphate rocks also undergo a washing process in advance of other processes. In addition, phosphate must first be transformed into a slurry through the adaptation process in order to be transported by pipeline. Through various processes, changes in the supply chain impact the water and energy consumed and, consequently, the CO2 emitted. The supply chain is determined by the quality and size of the phosphate rock, which in turn depend on the phosphate content at the time of extraction, ranging from very low to high. High-quality phosphate rock is transported to a drying process from which it is either marketed or chemically transformed into fertilizers at the manufacturing site. Low- to medium-quality phosphate rock undergoes washing, drying, grinding, and flotation processes to increase the phosphate content.

The fertilizer manufacturing site also has specific functional processes related to its products, which are fusion (F), sulfuric acid (ACS), phosphoric acid (ACP 29 %), concentrated phosphoric acid (CAP 54 %), and manufactured fertilizer. Phosphate transported from the mining area is used in the ACP process to manufacture phosphoric acid. In the CAP process, phosphoric acid concentration is increased from 29 % to 54 %, and then it is used either to manufacture fertilizers or directly exported. An additional chemical process may be used to manufacture fertilizers using phosphoric acid and other materials. These manufactured fertilizers are highly interlinked; the increase in fertilizer production is associated with the increased use of ACS, ACP, and phosphate. The phosphate industry produces and exports different types of fertilizers: monoammonium phosphate (MAP), triple superphosphate (TSP), ammonium phosphate sulfate (ASP), nitrogen (N)-phosphorus (P)-potassium(K) (NPK), diammonium phosphate (DAP), and nitrogen (N)-phosphorus (P)-sulfur (S) (NPS). Each type is produced using different combinations of materials.

2.2.2. Water and energy consumptions in mining and manufacturing areas

The processes in integrated supply chains consume water and energy, and the WEF-P tool applies to water and energy footprints, which indicate the quantity of water or energy consumed in various sub-processes in integrated supply chains (Fig. 4). The WEF-P tool uses historical data (from 2015) to estimate the average footprint value and the relationship between water and energy consumption and phosphate production. The technical details of each process are specific and aggregated into additional functional processes. Each process has a specific footprint based on field data and can be used monthly or as significant changes in capacity occur in the functional processes. First, we analyzed the relationship between the output of each process and water (or energy) consumption. Second, the WEF-P tool considered water transportation and energy consumption by trains and pipelines. In particular, transportation by train is related only to fuel consumption, such as diesel consumption. However, the pipeline station consumes electricity for the operating pipeline, and freshwater is transported with slurry. The pipeline should be full of materials such as slurry, but it is impossible to fill the pipeline with slurry; thus, the pipeline works to transport slurry and freshwater alternatively. Therefore, the total water (or energy) consumption in mining areas includes not only the water (or energy) used in processes but also that used in transportation systems, and it was calculated using Eqs. (1)–(5).

$$WC_{mining\ area} = \Sigma_i^n (P_i \times WFP_i) + WC_{pipeline\ station} \tag{1}$$

$$WC_{pipeline\ station} = P_{slurry} \times WFP_{pipeline\ station} \tag{2}$$

$$EC_{mining\ area} = \Sigma_i^n (P_i \times EFP_i) + EC_{pipeline\ station} + EC_{train} \tag{3}$$

$$EC_{pipeline\ station} = P_{slurry} \times EFP_{pipeline\ station} \tag{4}$$

$$EC_{train} = P_{phosphate\ rock} \times EFP_{train}, \tag{5}$$

where $WC_{mining\ area}$ (m^3) is the total water consumption in the mining area, $EC_{mining\ area}$ (MWh or gallon) is the total energy consumption in the mining area, and P_i (tons) is production from each process (i) in mining areas such as mining, screening, washing, flotation, and drying. WFP_i (m^3/ton) and EFP_i (MWh or gallon/ton) are the water and energy footprints, respectively, in each process (i). $WC_{pipeline\ station}$ (m^3) is the water consumption in the pipeline station, $EC_{pipeline\ station}$ (MWh or gallon) is the energy consumption in the pipeline station, and EC_{train} (MWh or gallon) is the energy consumption by train to transport phosphate rock to the manufacturing area. P_{slurry} and $P_{phosphate\ rock}$ (tons) are the production of slurry and phosphate rock, respectively. $WFP_{pipeline\ station}$ (m^3/ton) is the water footprint at the pipeline station in the mining area. $EFP_{pipeline\ station}$ and EFP_{train} (MWh or gallon/ton)

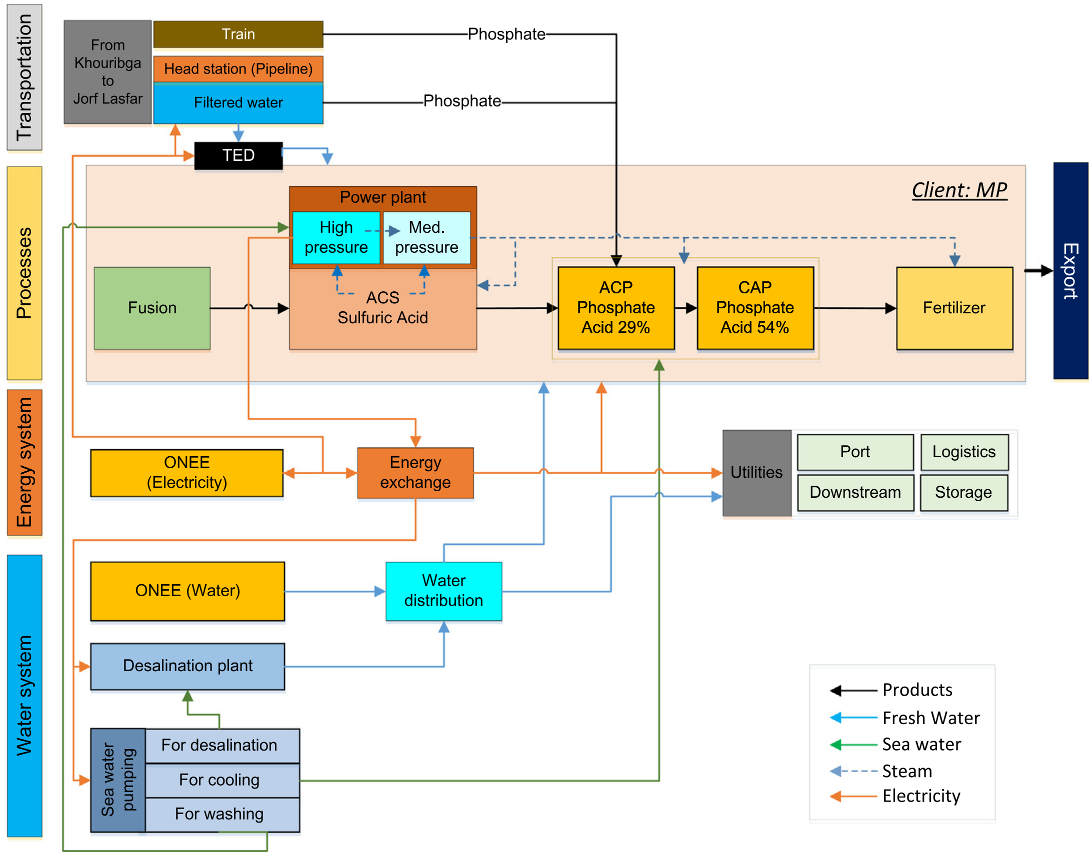

Fig. 4. Water and energy flows based on product supply chain in the industrial area.

are the energy footprints in the pipeline station and transportation by train, respectively.

Water consumed at pipeline stations in mining areas indicates the transported water used in the manufacturing area. In addition, the water embedded in the slurry is extracted and used to produce fertilizers in the manufacturing area. Therefore, we calculated the volume of water transported by the pipeline, including the embedded water in the slurry, as shown in Eq. (6).

$$WT_{tranportation} = WC_{pipeline\ station} + W_{slurry}, \tag{6}$$

where $WT_{tranportation}$ (m^3) is the total volume of water transported from mining to manufacturing area by pipeline, $WC_{pipeline\ station}$ (m^3) is the water consumption in the pipeline station, and W_{slurry} (m^3) is the volume of embedded water in the slurry.

Water consumption in the pipeline station is not involved in the manufacturing area, but energy use in desalination plants and pipeline terminals is included, as shown in Eqs. (7) and (8). In particular, desalination facilities are important water suppliers in manufacturing areas and consume electricity to produce freshwaters, such as the trade-off between freshwater supply and energy consumption. We surveyed the desalination facility and pipeline terminal station in the manufacturing area and applied their energy footprints to estimate the energy consumption, as shown in Eqs. (9) and (10).

$$WC_{manufacturing\ area} = \Sigma_j^n \Sigma_i^m \left(P_{i,j} \times WFP_i\right) \tag{7}$$

$$EC_{manufacturing\ area} = \left\{\Sigma_j^n \Sigma_i^m \left(P_{i,j} \times EFP_i\right)\right\} + EC_{desalination} + EC_{pipeline\ terminal} \tag{8}$$

$$EC_{desalination} = WG_{desalination} \times EFP_{desalination} \tag{9}$$

$$EC_{pipeline\ terminal} = P_{slurry} \times EFP_{Pipeline\ terminal}, \tag{10}$$

where $WC_{manufacturing\ area}$ (m^3) is the total water consumption in the manufacturing area and $EC_{manufacturing\ area}$ (MWh or gallon) is the total energy consumption in the manufacturing area, where i is the process for the final product fertilizer and j is the type of fertilizer. WFP_i (m^3/ton) and EFP_i (MWh or gallon/ton) is the water and energy footprints, respectively, in each process (i). $EC_{desalination}$ (MWh or gallon) is the energy consumption of desalination plants in manufacturing areas, $WG_{desalination}$ (m^3) is the volume of desalinated water in the manufacturing area, and $EFP_{desalination}$ (MWh or gallon/ton) is the energy footprint of desalination. $EC_{pipeline\ terminal}$ (MWh or gallon) is the energy consumption at the pipeline terminal station in the manufacturing area, P_{slurry} (tons) is the production of slurry, and $EFP_{pipeline\ terminal}$ (MWh or gallon/ton) is the energy footprint of the terminal station.

2.2.3. Water and energy supply from national water and energy facilities

The main function of the WEF-P tool is to assist with resource allocation and trade-off decisions. Therefore, it is imperative to understand, identify, and quantify the potential sources of supply for the allocated resources (water and energy): the amount of water, steam, and energy consumption used in each process. In the mining area, surface water is primarily supplied from a nearby dam (Aït Messaoud), which has a capacity of 45 million m^3/year, and the operation of this dam was not included in this study. Here are three sources of water supply in the manufacturing area: freshwater transported from the mining area via pipelines, desalinated water, and water supplied by the National Electricity and Water Company (ONEE). The desalination plant has a plan for water allocation to each client, and availability or limitations are adjusted by setting a “target of desalination water supply (%)”. Currently, the maximum target supply for the phosphate industry is 60 % of the total capacity (3 million m^3/month) of the desalination plants. Another water supplier is the terminal station of the mining area: effectively, water is transferred from the mining area through the slurry pipeline and then extracted from the slurry; this water quantity is, therefore, dependent on the amount of slurry transported by the pipeline. ONEE is a public water supply system that supplies water to a given client upon request if the desalination plant and pipeline station cannot supply sufficient water. The use of ONEE to supply water is strongly related to water security in industrial areas. This study assumed that the highest priority water source was the slurry transported through the pipeline station. Once this water is distributed to clients, the secondary source is from the desalination plant, and if more water is needed, it is supplied by ONEE, as shown in Eq. (11).

$$WS_{ONEE} = WC_{manufacturing\ area} - WT_{pipeline} - WG_{desalination}, \quad (11)$$

where WS_{ONEE} (m^3) is the volume of water supplied from ONEE, $WC_{manufacturing\ area}$ (m^3) is the total water consumption in the manufacturing area, $WT_{pipeline}$ (m^3) is the volume of water transported from the mining area to the manufacturing area by pipelines, and $WG_{desalination}$ (m^3) is the volume of desalinated water in the manufacturing area.

Both mining and industrial areas receive energy from fossil fuels or from electricity supplied by ONEE. In the mining area, all electricity is supplied by ONEE, but in the manufacturing area, each client includes a power plant that generates electricity using steam (both high- and medium-pressure steam) produced by the ACS process. In the case of MP, the largest client in Jorf Lasfar; 57 % of the total steam production is high-pressure steam, 43 % is medium-pressure steam. Ninety percent of the total high-pressure steam was used to generate electricity, and 85 % of the consumed high-pressure steam was then converted to medium-pressure steam. Utilities such as desalination plants, water treatment, and pipeline stations also consume electricity outside phosphate production processes. If a client does not have sufficient electricity from the power plant, it requests additional electricity from the Plant for Distribution of Electricity (PDE), which supplies the shortfall. PDE is a type of "control tower" for electricity exchange between clients. ONEE bridges any shortage and receives any surplus. The electricity exchange between clients and ONEE is calculated in the tool as a function of the production of electricity in the power plant and the consumption of electricity by the manufacturing area; therefore, the electricity supply is calculated by

$$ELS_{ONEE} = ELC_{manufacturing\ area} - ELG_{power\ plant}, \quad (12)$$

where ELS_{ONEE} (MWh) is the electricity supplied from ONEE, $ELC_{manufacturing\ area}$ (MWh) is the total electricity consumption in the manufacturing area, and $ELG_{power\ plant}$ (MWh) is the electricity generation in power plants using high-pressure and medium-pressure steam.

2.2.4. Direct and indirect CO_2 emissions by energy use

CO_2 emissions are important when assessing the environmental impact of phosphate production. These emissions are caused by burning the fuels used in the production process and during the generation of electricity (Table 1). When burned, fossil fuels (gasoline, diesel, coal, and so on), produce direct CO_2 emissions. Indirect CO_2 emissions are also related to the *source fuel* used to generate electricity from an external supplier (i.e., ONEE), and indirect emissions also occur in the generation of electricity using other (non-fossil) sources, such as hydroelectric energy, wind power, or solar energy. One gallon of gasoline used by machinery or a facility produces 9.8 kg of direct CO_2 emissions. A power plant burning only coal to generate electricity emits 1026 tons of CO_2 per 1 kWh. Renewable (non-fossil) electricity emits only 15.8 tons of CO_2 per 1 kWh. A survey of sources of electricity generation in Morocco indicated that coal is the main fuel for power generation (43.4 % of the national production).

Table 1
CO_2 emission by burning fuels and generating electricity.

CO_2 emission by burning fuel		CO_2 emission by generating electricity		
Sources	CO_2 emission[a] (kg of CO_2/gallon)	Sources	CO_2 emission by sources[a] (tons of $CO_2/10^3$ MWh)	Proportion of sources[b] (%)
Gasoline	9.8	Coal	1026	43.4 %
Diesel	11.2	Petroleum	1026	25.3 %
		Natural gas	504	22.7 %
		Hydroelectricity	19.7	6.9 %
		Renewables	15.8	1.7 %

[a] U.S. Energy Information Administration (https://www.eia.gov) (USEIA).
[b] International Energy Agency (2014).

$$DCO_2 = \Sigma_i^n CFF\_F_i \times FC_i \quad (13)$$

$$InDCO_2 = \Sigma_j^n CFP\_E_j \times ELC_j, \quad (14)$$

where DCO_2 (tons) is the direct CO_2 emissions and $InDCO_2$ (tons) is the indirect CO_2 emissions. CFF_F_i (tons/gallon) is the CO_2 footprint of the burning fuel, FC_i (tons/gallon) is the fuel consumption by the machine excluding fuel use for electricity generation, and i is the type of fuel such as diesel or gasoline. CFP_E_j (tons/MWh) is the CO_2 footprint generated by electricity, ELC_j (MWh) is the electricity consumption, and j is the source of electricity generation, such as coal, petroleum, natural gas, solar and wind energy, and hydropower.

3. Results and discussion

3.1. Application of operation scenarios combining final production, transportation, and desalination

Increasing the amount of fertilizer products and changing the transportation system from trains to pipelines were defined as top priorities for the phosphate industry in Morocco. In particular, the change in the mode of transport affects both the direct energy consumption and water consumption. It also affects the entire supply chain within the mining site because dried phosphate must be transformed into slurry for pipeline transport. Thus, the transportation scenarios were adapted to indicate pipeline use.

The scenario used in this study is based on the amount of product produced and the mode of transport. This is because changes in the amount of product produced is directly related to the water and energy consumption in the overall processes, and changes in the mode of transport results in structural changes in the supply chain. Increases in production were determined by the agreement with the OCP Group of Morocco to be the annual production goal set by the OCP Group. The transport pipeline has already been established by the OCP and is currently used in combination with the train system. However, the scenario of 100 % pipeline transport system was used in this study, since the future plan calls for the use of pipelines without train transport.

Table 2 shows scenarios combining production and transportation: the first one relates to operation in 2017, which is set as scenario #1. For example, 698,000 tons/month of phosphorous fertilizers were produced in the manufacturing area, 2,040,208 tons/month of raw phosphate were transported from the mining to the manufacturing area, and 60 % of raw phosphate was transported by pipeline in the form of slurry. Scenario #2 relates to the subsequent change in the mode of transport from train to pipeline by an increase of transportation of slurry. For example, the proportion of phosphate slurry in total raw phosphate increased from 60 % to 80 % in scenario #2. The more transportation by pipeline accompanies the more water and electricity use in pipeline station but derives less fuel use by train. In addition, scenario #2 considers more usage of desalinated water in the manufacturing area. In 2017, the operation rate of the desalination facility was 60 % of maximum capacity, and we applied the maximum operation in the scenario #2. The usage of desalinated water could bring more energy use in desalination facilities, but it could contribute to public water saving.

3.2. Holistic assessment of operation scenarios on mining and manufacturing areas

The sub-products for final exports were calculated using the WEF-P tool through their supply chains. Final products, such as fertilizers, require input materials from previous processes and raw phosphate, whether slurry or

Table 2
Scenarios through combination of production, transportation, and desalination facility.

Scenario	Export of raw phosphate (tons/month)	Production of fertilizer (tons/month)	Phosphate transported by pipeline	Operation of desalination facility
Scenario #1 (operation in 2017)	1,848,000	698,000	60 % of total phosphate	60 % of maximum capacity
Scenario #2	1,848,000	698,000	80 % of total phosphate	100 % of maximum capacity

rock. Scenario #1 includes a change in the mode of transportation from the train to the pipeline and an increase in production. Approximately, 2 million tons of raw phosphate was mined, and 60 % of total phosphate was transformed into slurry and transported by pipelines. Scenario #2 had the same amount of raw phosphate and fertilizers, with the only difference being in the amount of slurry. Compared to scenario #1, approximately, 482,949 tons/month of raw phosphate was transformed into slurry.

Based on the sub-products and resource footprints of the processes, we estimated water and energy consumption in mining and manufacturing areas. In scenario #1, approximately, 2,026,636 m^3 of water was required for processes in the mining area. The manufacturing area has different processes in the supply chain system compared to those in the mining area; thus, the total water consumption in the manufacturing area was 5,231,689 m^3 in scenario #1. Both areas were connected through the transportation process; for example, they shared water transported through the pipeline. In particular, 427,821 m^3 of water was transported to the pipeline terminal in the manufacturing area by the pipeline, and it was used for producing fertilizers in the manufacturing area in scenario #1. Scenario #2 indicates that the pipeline transported more raw phosphates as slurry than that of scenario #1. Therefore, the water transported in the pipeline station decreased from 427,821 m^3 in scenario #1 to 212,762 m^3 in scenario #2 because more slurry filled the pipeline. However, slurry production involves adaption processes, which are the main water consumers in mining areas. Therefore, the change of phosphate rock to slurry can cause more water use. Fig. 5(a) shows that the amount of water in the mining area increased from 2,026,636 m^3 to 2,533,588 m^3 because the total slurries produced increased from 1,151,029 tons to 1,633,978 tons. Accordingly, transportation by pipelines can save water in pipeline stations; however, more water is required in the adaptation processes. Scenario #2 had the same amount of fertilizers produced in the manufacturing area as scenario #1; thus, there was no change in water consumption in the manufacturing area.

In the case of energy, the consumption of fuels and electricity is quite different in mining and manufacturing areas because of the different processes. Fig. 5(b) shows the fuel consumption in mining and manufacturing areas. In the mining area, 3,186,934 gallons of fuels such as diesel and gasoline were required in scenario #1, which was two times larger than the fuel consumption in the manufacturing area because raw phosphate goes through a "drying process" to produce dried phosphate, which consumes many fuels in the mining area to transport raw phosphate by trains. In addition, scenario #1 indicates that 40 % of raw phosphate was transported by a train, and we estimated that 527,703 gallons of fuel were used by the train. Scenario #2 derives the decrease in the amount of phosphate rock produced by the dry process; thus, the total fuel consumption decreased from 3,186,934 gallons in scenario #1 to 2,410,751 gallons in scenario #2. In addition, the fuel used by the train also decreased to 241,086 gallons, which means 286,617 gallons of fuel savings compared to that of scenario #1. However, in the manufacturing area, fuel consumption occurs during the final processing of fertilizers; changing the mode of transport from train to pipeline does not affect the fuel consumption in the manufacturing area. Generally, fuel consumption in the mining area is much larger than that in the manufacturing area, and the change in transportation modes, such as trains and pipelines, affects fuel consumption in mining areas more than in manufacturing areas.

However, most processes in the manufacturing area are strongly dependent on electricity rather than fuel energy. Fig. 5(c) shows the electricity consumption in mining and manufacturing areas. For example, the total electricity consumption in the mining area was 45,241 MWh, including the electricity used in the pipeline station (7416 MWh) in scenario #1. However, the electricity consumption in the manufacturing area is 161,670 MWh, which is 3.6 times larger than that in the mining area. The electricity consumption in the mining area increased with an increase in slurry production in scenario #2 because the adaptation processes and pipeline stations use more electricity. Accordingly, the electricity consumption in scenario #2 increased to 48,851 MWh. In summary, the change in transportation mode from train to pipeline could decrease fuel consumption but increase electricity consumption in mining areas. The increase in the amount of fertilizers is more related to the increase in electricity and fuel consumption in the manufacturing area.

Mainly, production management in the industry is followed by economic benefits, but it is related to socio-economic and environmental impacts, such as public resource security and CO_2 emissions. For example, public water saving in manufacturing areas through desalinated water use is related to trade-offs with energy use for desalination facilities. In addition, pipeline transportation could benefit water savings in the manufacturing area because freshwater and embedded water in the slurry are transported with slurry. However, we should consider water for transportation and energy for pipeline operation, which is regarded as a trade-off impact on the mining area. CO_2 emissions could also be considered an important variable in the trade-off analysis of scenarios; for example, electricity consumption in desalination facilities and pipeline stations would cause increasing CO_2 emissions. Therefore, decisions regarding production, transportation, water supply, and energy supply should be considered in the context of inter-relationships among these managements, economic benefits, water-energy security, and CO_2 emissions.

Fig. 6 shows the sources of water supply in manufacturing. For example, 410,173 m^3 of overflow water was supplied from the pipeline terminal station, including the freshwater transported by the pipeline from the mining area and embedded water in the slurry. Accordingly, water from the pipeline terminal station belongs to the mining area; thus, it would impose a burden on water security in the mining area, but it would contribute to water savings in the manufacturing area. In water management, pipeline transportation should be considered under the trade-off between water use in mining areas and water saving in manufacturing areas. If mining areas have plenty of water from dams or rivers, the transportation of water by pipelines to the manufacturing areas would be helpful for water and energy management in the manufacturing areas because one of the main water resources is desalinated water, and energy is essential for operating desalination facilities. In the manufacturing area, ONEE supplies freshwater to produce fertilizers. For example, the total water consumption in the manufacturing area was 5,231,689 m^3; thus, 1,275,279 m^3 of water from the pipeline terminal station and 1,545,672 m^3 of desalinated water were supplied; however, 2,410,738 m^3 was required. ONEE supplies the lack of water from the public water supply facility, which varies according to the regional water security of Jorf Lasfar. Therefore, desalinated water use, water transportation by pipelines, and water embedded in the slurry can save public water in the manufacturing area. Looking at scenarios #1 and #2, the amount of slurry transported in the pipeline and the capacity of the desalination facility increased. In scenario #2, the water supply from the terminal station and desalination facility increased to 1,606,539 m^3 and 2,227,681 m^3, respectively. Therefore, the water supply from ONEE decreased from 2,410,738 m^3 in scenario #1 to 1,397,470 m^3 in scenario #2. This saved water can be utilized by other water consumption sectors in the manufacturing area.

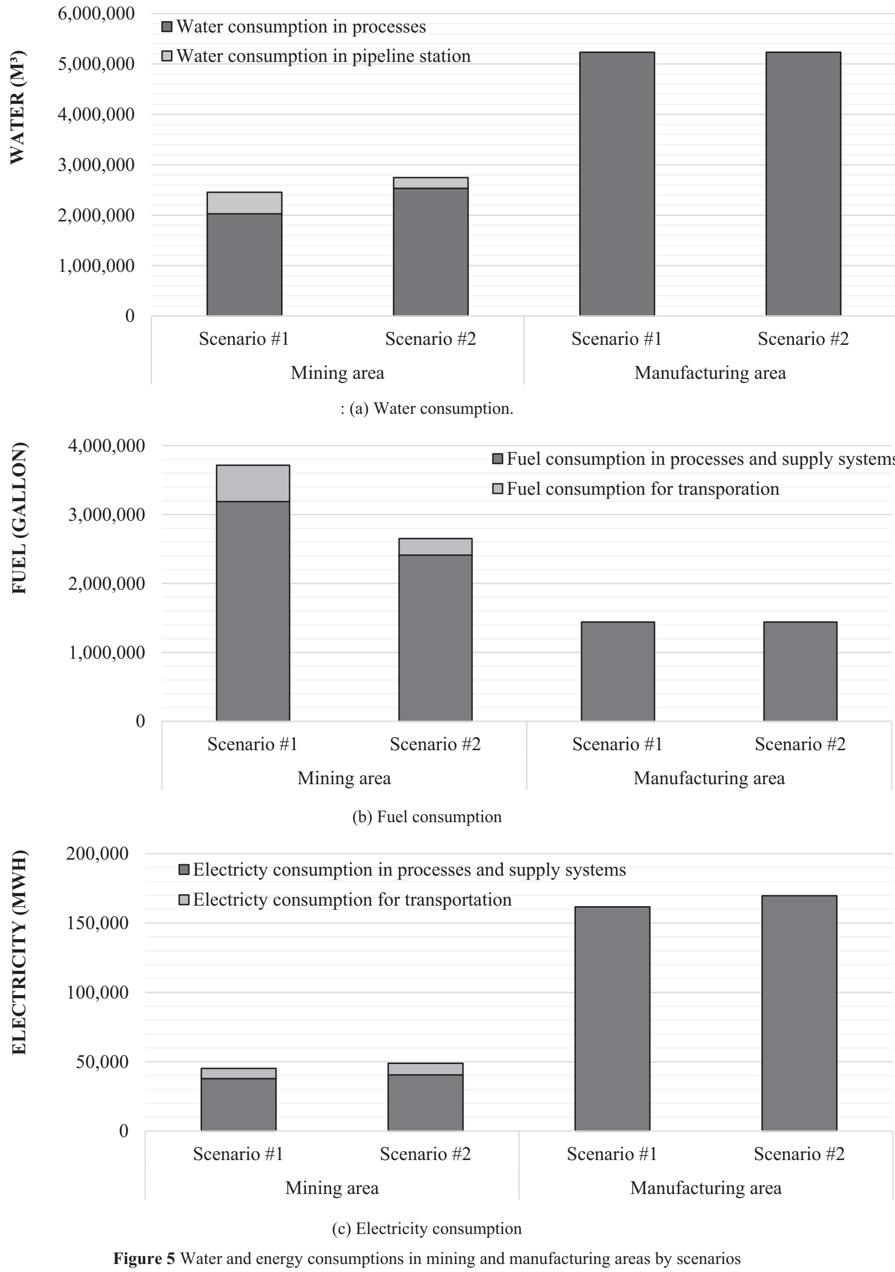

Fig. 5. Water and energy consumptions in mining and manufacturing areas by scenarios.

However, increasing desalinated water supply and slurry transportation could cause more electricity consumption in terminal stations and desalination facilities. The desalinated water supply could decrease the supply from ONEE and increase public water security, but more electricity is needed for operating desalination facilities. For example, in scenario #1, approximately 25,404 MWh was supplied from ONEE, which increased to 33,477 MWh in scenario #2 (Fig. 7) because of the increase in desalinated water use and transportation of slurry by pipelines. The changes in electricity supply from ONEE are also related to CO_2 emissions. In the manufacturing sector, the power plant is the major electricity provider; however, it does not emit CO_2. ONEE is the only public plant in Jorf Lasfar that uses fossil fuels and emits CO_2. Fig. 8 shows the direct and indirect CO_2 emissions from energy use in mining and manufacturing areas. In scenario #1, direct CO_2 emissions were 14,639 tons, and indirect CO_2 emissions were 21,365 tons, but most of the electricity was provided by local power plants inside the manufacturing area, and the electricity supply from ONEE was 25,404 MWh. In mining areas, CO_2 emissions are also an important variable in the slurry transportation by pipelines. In scenario #1, 87,892 tons of CO_2 were emitted, but scenario #2 could reduce CO_2 emissions (79,692 tons of CO_2) in the mining area. In particular, direct CO_2 emissions were significantly decreased by reducing fuel use. Approximately, 11,903 tons of CO_2 were saved by changing the amount of slurry from 1,151,029 tons (scenario #1) to 1,633,978 tons (scenario #2).

In Morocco, the phosphate industry is a major consumer of water and energy. This study provides an assessment tool that links the industrial processes, resource, and sustainability of multiple scenarios of Morocco's phosphate industry. To sum up, A given scenario can reflect potential water or energy security issues differently in mining and manufacturing areas. While the increase in phosphate production stress on water and electricity resources in the mining area, more water and electricity will be available in the manufacturing area and, hence, release pressure on the water and electricity resources in the Jorf Lasfar area. Therefore, we need

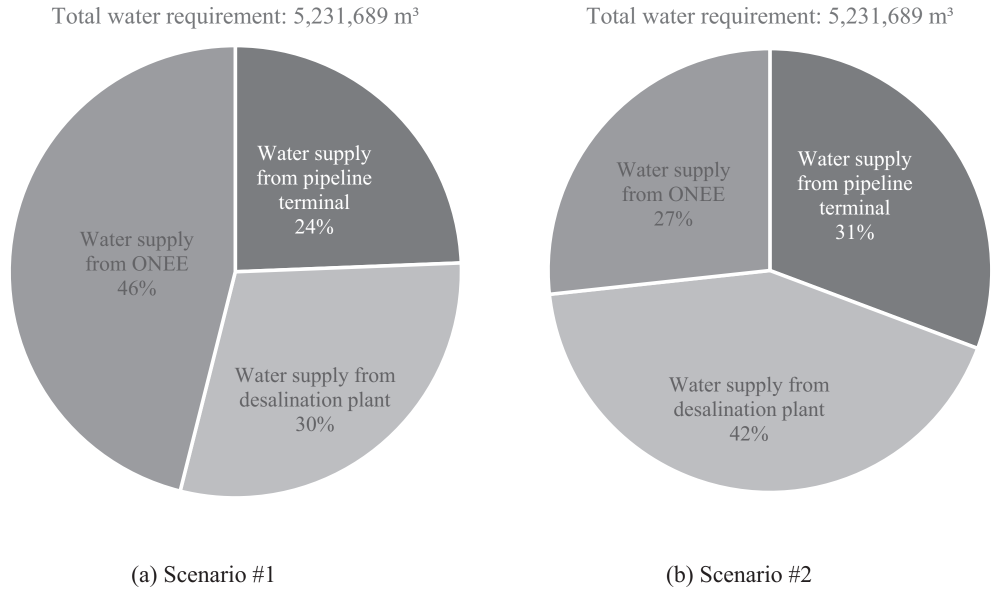

Fig. 6. Water supply in the manufacturing area.

to consider these trade-offs when we set policies related to phosphate production, which could provide useful information regarding the holistic impacts of scenarios to decision-makers.

4. Conclusions

The WEF-P tool was developed to allow its users to holistically assess the sustainability of phosphate production and its transport from mining to industrial areas in terms of resource (water and energy) availability and CO_2 emissions. The tool was developed in three stages:

(1) **Identification of the integrated supply chain** between resources: Flow diagrams were created to reflect the processes used in phosphate production;
(2) **Application of footprints** quantifying the associated resource consumption in phosphate production; and
(3) **Developing a scenario assessment tool** that creates scenarios to provide data in support of trade-off analysis and decision making that enables a comparison of scenarios.

The strength of the WEF-P tool lies in its flexible supply chain management. The existing Nexus based on crops analyzes synergy and trade-offs between resources with focus on the total crop production or the total water resource used. However, the WEF-P tool used in this study analyzes how water and energy consumption changes during the whole process of production and transport, and how the connection between water and energy changes when the supply chain and production rate are modified. Thus, more detailed production processes are introduced into the Nexus through inclusion of supply chain within the LCA. Furthermore, if the place of acquiring raw materials is different from the place of manufacturing the final products, the impact of consequent changes in transport system on individual regions as well as the combined inter-regional system can be assessed.

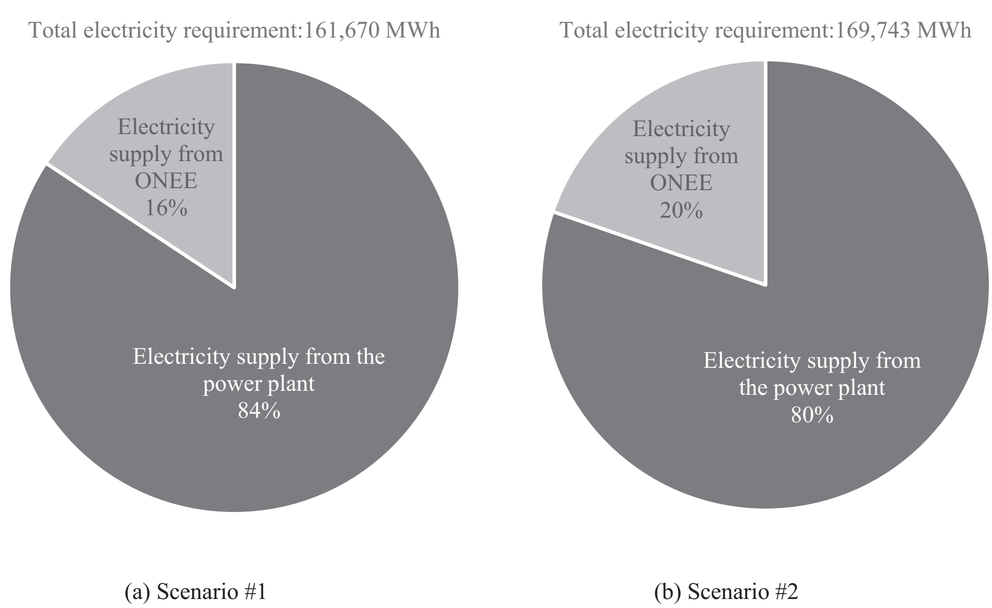

Fig. 7. Electricity supply in the manufacturing area.

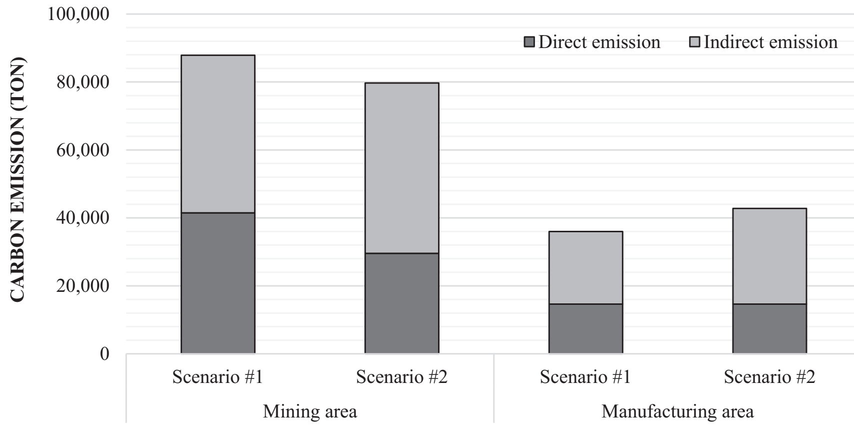

Fig. 8. CO_2 emission by energy use in mining and manufacturing areas.

In summary, LCA used in this study is an essential methodology for development of process-based Nexus rather than environmental impact assessment. New processes can be adapted to the supply chain, and the footprints of the given processes can be adjusted as phosphate production occurs. New phosphate production lines can be integrated using this tool. The WEF-P tool holistically assesses trade-offs and assists in demonstrating the potential impacts by making the data available to illustrate prospective outcomes dependent upon the choices (trade-offs) made by stakeholders, thereby contributing to sustainable decisions. Various scenarios related to the phosphate industry can be applied to the tool to include production, water and energy consumption, and CO_2 emissions. The tool developed includes

- quantifying the resources allocated to achieve established goals,
- assessing resources available to achieve the production goals, and
- assessing the sustainability of those goals as established for each scenario.

However, there are limitations to the tools relating to data quality and collection, system definition, temporal boundaries, and process modeling. The results were significantly influenced by the quality and availability of the data. For example, the footprints and supply chain in the WEF-P tool rely on survey data for the scale of phosphate mining or fertilizer production in the client industry. A single-year dataset was applied to develop the tool. Some of the data were assumed, and data specific to the factories in the industrial area were not included. The WEF-P tool is based on monthly operations, and the results do not represent the long-term impacts. In particular, this study has limitations in evaluating the environmental impact. The LCA applied in WEF-P is focused on the analysis of water-energy balance that results from changes in supply chains.

Nevertheless, The supply chain-based WEF-P tool developed in this study is expected to contribute to other studies as follows:

- Expand the Nexus concept to include processes within each resource variable
- Show impacts of changes in specific scenarios on the overall processes related to the Nexus system
- Allow changes in processes of resource management, as well as production for sustainability, to be reflected in decision making
- Expand the boundary of resource management by including transport of goods in the analysis
- Help enhance the industry's goals within national, regional, and international concerns.

CRediT authorship contribution statement

Sang-Hyun Lee: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Amjad T. Assi:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Rabi H. Mohtar:** Conceptualization, Methodology, Writing – review & editing. **Meryem Hamane:** Conceptualization, Methodology. **Pu Reun Yoon:** Writing – review & editing. **Seung-Hwan Yoo:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Data availability

Data resulting from this study are freely available by contacting the corresponding author.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding this publication.

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