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Sustainable production of hydrocarbon fields guided by full-cycle exergy analysis

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ABSTRACT

To mitigate the negative impacts of hydrocarbon fuels on climate change complementary decision tools should be considered when selecting or evaluating the performance of a certain production scheme. The exergy analysis can give valuable information on the management of the oil and gas reservoirs. It can also be used to calculate the CO_2 footprint of the different oil recovery mechanisms. We contend that the concept of exergy recovery factor can be used as a powerful sustainability indicator in the production of the hydrocarbon fields. The exergy-zero recovery factor is determined by considering exergy balance of full cycle of hydrocarbon-production systems and defines boundaries beyond which production of hydrocarbons is no longer sustainable. An example of the exergy analysis is presented in the paper.

1. Carbon-neutral fossil fuels

Fossil fuels are the major energy sources mainly because of their large volumetric energy density and ease of access and transport (Olah et al., 2009). The modern age owes much of its progress and welfare in the last century to fossil fuels. However, conversion of fossil fuels to consumable energy results in significant atmospheric emissions of CO_2 and is a major contributor to climate change (IPCC Report, 2007). With growing concerns about global temperature rise as well as other environmental issues, reliance on energy from fossil fuels, at least with the current production technologies, is not a sustainable solution for future energy requirements. The development of alternative renewable energy resources and carriers requires significant investments with a long-term commitment that must clear economic hurdles. Undoubtedly, in the long-term sustainable energy sources will be developed; however, in the shorter-term *transition period* the energy supplied from the existing fossil-fuel resources should aim to minimize the greenhouse-gas emission to limit the long-term climate changes while maintaining the world's energy supply.

Production of fossil fuels and in particular hydrocarbons from subsurface formations involves energy-intensive technologies, often leading to considerable greenhouse-gas emissions. Unfortunately, a significant fraction of energy is also “wasted” during the production period. The current *energy investment* (Carbajales-Dale et al., 2014) required to extract energy from fossil fuels is immense, for example when tertiary thermal or chemical enhanced recovery methods (Lake et al., 2014; Hassan et al., 2019) are applied. These considerations motivate the development of *carbon-neutral* production methods with (ideally) net-zero CO_2 emission (Wigley, 2006) during the *transition period* to maintain global temperature rise at levels below 2 °C (IPCC report, 2007). This is not to say that CO_2 cannot be produced but ideally the produced CO_2 should be utilized within the process cycle or elsewhere in the system. In order to achieve this goal the following approaches are proposed: (1) adjustments and modifications to current technologies. This can be achieved by improving the efficiency of the whole system or by removing/replacing/optimizing the energy-intensive components. The optimization schemes should consider the *full-cycle analysis* of the entire production system, (2) (timely) integration of (available) renewable energy sources, (3) development of alternative recovery methods using *novel carbon neutral chemicals* (for example biosurfactants and biopolymers, Hassan et al., 2019) or *hybrid technologies* (steam generated by solar energy for thermal EOR, Bierman et al., 2014), (4) utilization *and* storage of produced carbon dioxide (CO_2 EOR with low energy-intensive capture method or CO_2 hydrogenation to produce methanol or dimethyl ether using renewable energy sources, Matzen en Demirel, 2016; Martin, 2016), and (5) utilization of waste (material and energy) streams. Here we focus on the first approach and explain an exergy-based approach that can be used as a measure of sustainability of the hydrocarbon-production systems. An example of the analysis will also be presented in the paper.

2. Decision tools

Hydrocarbon-containing fields are usually screened for several

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technologies, one of which is eventually selected for development of an "efficient" concept or strategy to extract the enormous energy stored in hydrocarbons. The decision is often made based on project profitability (measured by some economic measures such as discounted cash flow or net present value, NPV) and amount of recovered hydrocarbon, measured by "sweep" efficiency (Lake et al., 2014) or the hydrocarbon recovery factor defined by

$$E_{RF} = \frac{S_h^{ini} - S_h}{S_h^{ini}}, \tag{1}$$

where, S_h is the fraction of the pore volume filled with the hydrocarbon and the superscript *ini* denotes the initial conditions. The largest NPV is not necessarily obtained from the maximum E_{RF} (van Essen et al., 2009) and more importantly large NPV and E_{RF} values are not always energetically favorable. In fact, NPV largely depends on the duration of the project and can be adjusted by the discount rate, (volatile) commodity prices, subsidies and other socioeconomic incentives, which vary from place to place and even during execution of the project. Therefore, NPV-driven decisions may not always lead to lower levels of greenhouse gases in the atmosphere, which indicates the hydrocarbon-production technologies should be benchmarked using new decision tools considering their energy-consumption and carbon-emission levels.

2.1. Full-cycle exergy analysis of hydrocarbon production systems

It is proposed that sustainable development of any hydrocarbon-production scheme should consider the energy inputs and energy wastes using a *system analysis*. The first step in carbon-neutral production of hydrocarbons is accordingly to analyze the *life cycle of material and work streams* from environmental, economic, socio-cultural and sustainability perspectives. From a thermodynamics perspective, this could be achieved by considering the *exergy balance* (Sato, 2004; Szargut et al., 1988; Szargut, 1989; Eftekhari et al., 2017; Hassan et al., 2019) over a given control volume. Exergy is the maximum work gained from an energy stream when it is brought from its initial state (pressure, temperature, and composition) to a reference dead state (Sato, 2004). Unlike energy, which is conserved according to the first law of thermodynamics, *exergy* can be dissipated in a process because of irreversibility and generation of entropy.

Production of hydrocarbons contained in subsurface formations involves many complex processes (exploration, appraisal, drilling, production, refining, transportation, etc.) and its full-cycle analysis with detailed tracking of the energy flow demands a lot of data/information, which might not be readily available. The system can often be broken into subsystems with individual components. It can then be simplified by performing an initial elementary analysis to identify the main elements for a full-cycle analysis and optimization. The workflow of the proposed exergy analysis is shown in Fig. 1.

The exergy analysis of the hydrocarbon-production systems provides information on the location and scale of destroyed exergy (Nguyen et al., 2013). The results of the analysis can be used to design alternative systems/facilities/concepts and/or to make adjustments to the current production scheme by optimizing the process parameters.

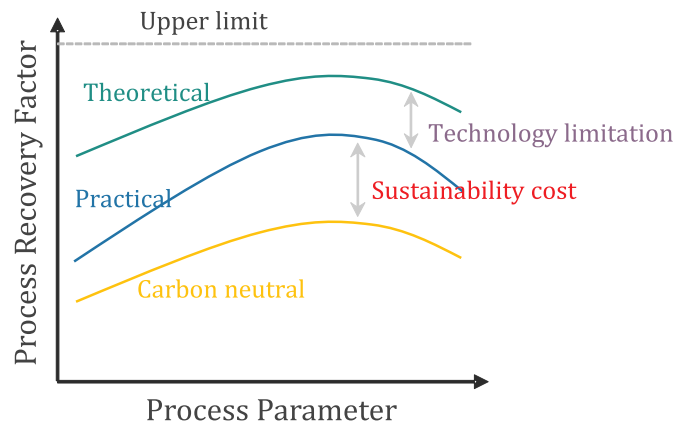

Fig. 2. Recovery factor versus process parameters, adapted from Eftekhari et al. (2012)Eftekhari et al. (2012). The end goal of component-based exergy analysis is to shorten the distance between carbon-neutral and theoretical efficiencies by optimizing/eliminating energetically-expensive processes or avoiding production of hydrocarbons that require large energy investment.

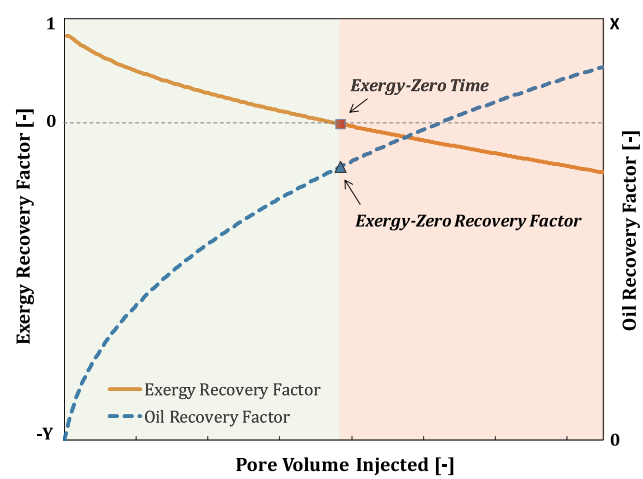

Fig. 3. An exemplary oil recovery factor (E_{RF}) history (left axis, dashed line) and its corresponding exergy-recovery-factor (Ex_{RF}) history (right axis, solid line). The project is not energetically sustainable after the *exergy-zero time* (corresponding to an *exergy-zero-recovery factor*), shown by red shaded area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

For example, in enhanced oil recovery techniques, the process parameter could be the volume of the injected chemicals. In the next section we will show that in water-injection improved oil recovery the water cut or water utilization factor (the volume of water required to produce unit volume of oil) could be the optimized parameters. The component-based exergy analysis can quantify the difference between the theoretical (i.e. ideal or reversible) and the practical (irreversible) process

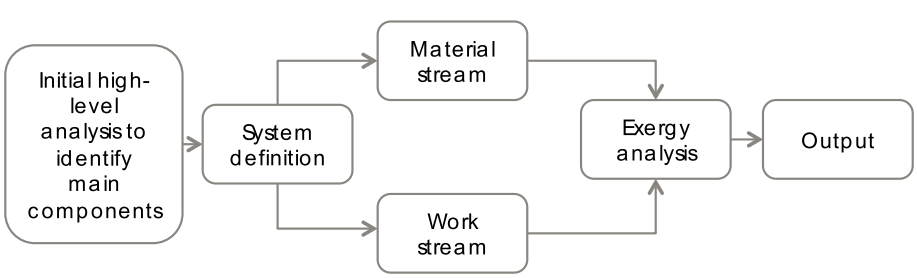

Fig. 1. Workflow of an optimization process based on the exergy analysis: the output is list of exergy-intensive components/processes and offers the basis for a more sustainable production system.

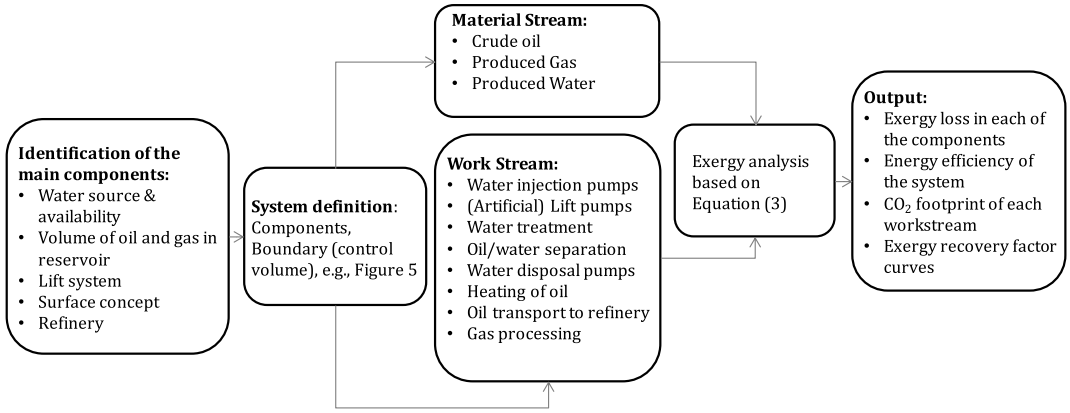

Fig. 4. Summary of the main elements of the exergy analysis for the water-injection process.

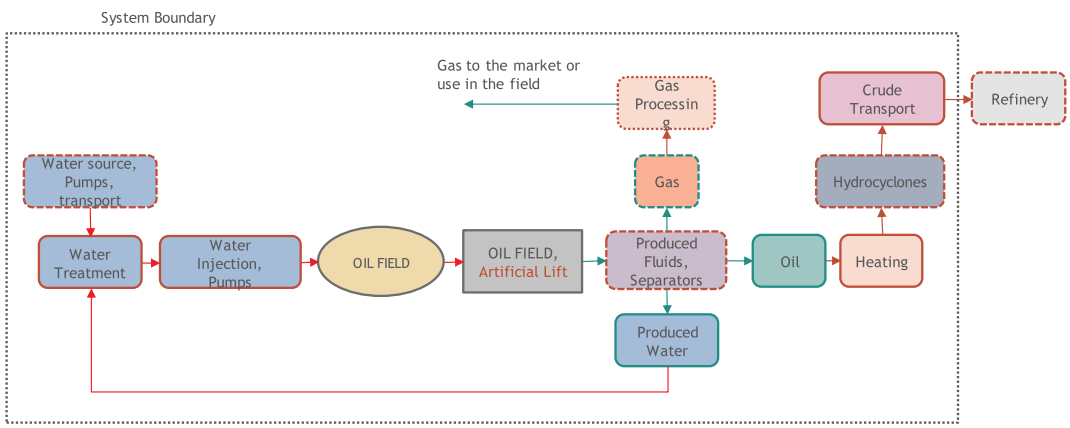

Fig. 5. An example of the system definition for a water-injection process. The components in the dashed boxes are identified to be negligible exergy investments.

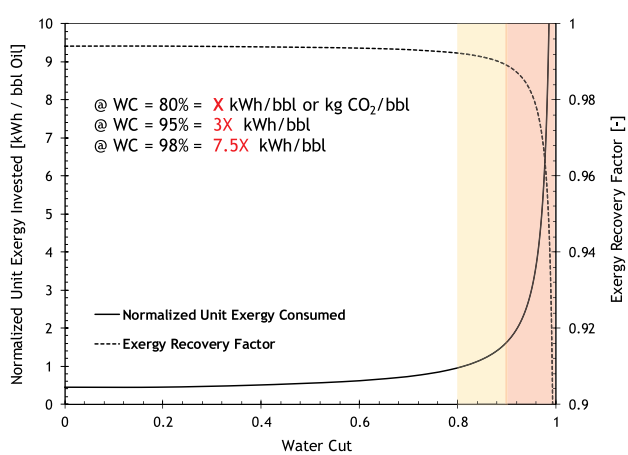

Fig. 6. Example of exergy-recovery factor and unit exergy invested to produce unit volume of oil for a water injection project. Small reductions in the water cut can make the oil production more sustainable and cleaner.

efficiency. The outcome leads to a more sustainable production or optimal reservoir management scenario. This might not always be the scenario with maximum hydrocarbon volumes or exergy gain. Nevertheless, the result of the analysis will be a plan by which hydrocarbons are extracted with lowest possible exergy investment or CO_2 footprint. The end goal of the exergy analysis is to close the gap between the zero-emission (carbon-neutral) and theoretical efficiencies (Fig. 2). The exergy-based life cycle analysis of the hydrocarbon production should be performed in an *integrated inter-disciplinary* manner, i.e. by exploiting expertise of various (surface and subsurface) disciplines of energy and material sciences at multiple length and time scales. This will help understanding of the flow of energy in different stages of the production/consumption loop, which may also vary with time.

2.2. Exergy-recovery factor as a measure of sustainability in production of hydrocarbons

The efficiency of the production concepts can be evaluated using the *Exergy Recovery Factor* (Ex_{RF}), defined as

$$Ex_{RF} = \frac{\int_{t_1}^{t_2} (Ex_{gained} - Ex_{invested})dt}{\int_{t_1}^{t_2} Ex_{gained}\,dt}, \tag{2}$$

Ex_{RF}, which assumes values between $-\infty$ and 1, is a measure of the *wasted or lost exergy* (or quality of energy) of a system and can be used as a powerful sustainability index in analyzing hydrocarbon-production systems (including surface and subsurface processes), comparing various recovery mechanisms, defining more favorable operating conditions, and identifying the bottlenecks for further improvements. A negative Ex_{RF} implies that the invested exergy is more than the gained exergy and therefore such scheme is not sustainable. The "*weakest link*" in the loop is often outside of the (subsurface) reservoir, which has traditionally been in the center of relentless optimizations during production of hydrocarbons.

Fig. 3 is a schematic plot of Ex_{RF} and E_{RF} as a function of the dimensionless time or pore volume of the injection fluid. These plots can be made by considering the invested (work) and the gained (material) exergy streams of the applied recovery mechanism. Naturally, as time passes Ex_{RF} decreases, despite the increase in E_{RF}. This implies that as the lifetime of the hydrocarbon field increases, more energy is needed to extract a unit volume of the hydrocarbon. For some recovery

processes, after a certain time the amount of invested exergy can exceed the amount of the gained exergy, i.e., a negative Ex_{RF}, which indicates that a large amount of exergy is wasted (or lost) without performing useful work. Therefore, *every production scheme has an exergy-zero time corresponding to an exergy-zero-recovery factor, which is the maximum fraction of the in-situ hydrocarbon that can be sustainably produced*. Beyond this time the extraction of energy is not sustainable, even if hydrocarbons are produced with a positive NPV. The red shaded area in Fig. 3 should be avoided in production of hydrocarbons because the selected scheme emits significant amounts of CO_2 and wastes energy, which could otherwise be used to perform useful work in other sectors.

2.3. An example: water injection

We provide an example of exergy analysis for water-injection process, which is widely used to extract oil because of its low cost and simplicity. Following the workflow presented in Fig. 1, the main elements of this production method are summarized in Fig. 4, based on which an exemplary system (or boundary) is defined (Fig. 5). In the next step, the exergy of the individual components of the material (gained) and work (invested) streams is used to obtain the Ex_{RF} of the process. At this stage, only the main contributors to the exergy streams (shown in boxes with solid line in Fig. 4) are considered. The negligible components are identified either by calculations or based on the experience of the concept engineers. For instance, if the volume of the produced methane is negligible, the exergy recovery factor is obtained from

$$Ex_{RF} = \frac{\int_0^t Ex_{oil}^{ch}\,dt - \int_0^t (Ex_{water}^{pump} + Ex_{water}^{treatment} + Ex_{fluid}^{lift} + Ex_{oil}^{heating} + Ex_{oil}^{transport})dt}{\int_0^t Ex_{oil}^{ch}\,dt} \tag{3}$$

Exergy values are expressed in *kJ/kg*. The amounts of the injected and produced fluids (gas, water, and crude oil in m^3/s) are obtained from available analytical or numerical simulations considering subsurface and surface constraints. The exergy of the work streams can be obtained from thermodynamic relations. For example, the theoretical pump exergy rate is given by

$$\dot{E}x_{liquid}^{th,pump} = \dot{Q}\Delta P \tag{4}$$

with $\dot{Q}$ being the injection rate and ΔP the drawdown pressure. The practical exergy rate can then be obtained by accounting for the pump efficiency, η_{pump}:

$$\dot{E}x_{liquid}^{pr,pump} = \frac{\dot{Q}\Delta P}{\eta_{pump}} \tag{5}$$

Using the sum of the exergy invested in different components of the system and the amount of the produced hydrocarbons, the exergy footprint or the amount of exergy required to produce one barrel equivalent of the hydrocarbon (*kJ/bbl*) can be obtained. The amount of CO_2 emitted per produced barrel can then be obtained depending on the CO_2 footprint of the energy source. In this study we have assumed 650 gr CO_2/kWh, which is the average CO_2 footprint of electricity in the Middle East (International Energy Agency, 2015). Fig. 6 plots the exergy recovery factor and the unit emitted CO_2 as a function of water cut (or the water fraction of the produced fluids) for a water injection process. It appears that when the fraction of the produced water (water cut) is above 90% the increase in the invested exergy (and consequently the carbon footprint) becomes dramatic. Therefore, reductions in water cut and water management can lead to significant reductions in the invested exergy or emitted CO_2.

2.4. Final remarks

During the transition period, despite their negative impact on climate, hydrocarbon fuels will continue to remain major contributors to the global energy supply. Therefore, complementary decision tools should be considered to evaluate the environmental impacts and CO_2-emission levels of the candidate hydrocarbon-production systems. Here, we introduce the concept of exergy-zero recovery factor (or exergy-zero time) as an indicator to assess the sustainability of the hydrocarbon-production projects. It can be determined by *full-cycle exergy analysis* considering the main surface and subsurface elements of the development concept. This exergy invested in the whole system can also provide the CO_2 footprint of the (equivalent) barrel of the produced oil. Beyond the *exergy-zero recovery factor* or the *exergy-zero time* the production of hydrocarbon is no longer sustainable.

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