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Future oil extraction in Ecuador using a Hubbert approach

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ABSTRACT

Hubbert based models to project future oil extraction in Ecuador were developed. Two values of ultimate recoverable resources (URR) (7860–10,700 million barrels (MMbbl)) are applied to 16 models, considering symmetric and asymmetric Hubbert models and one and two cycles under top-down and bottom-up approaches. Models are discussed based on the best fit to historical data, and year and value of maximum extraction. The peak oil extraction obtained ranges between 196 and 215 MMbbl and would be reached in the years 2014–2025. An analysis of the implications of extraction models in a Business as Usual and Alternative oil demand scenarios up to 2035 was performed. Ecuador could become a net oil importer between 2024 and 2035, depending on the model and demand scenario. Economic oil trade balance could be seriously affected, decreasing from a current positive value of around 2 billion USD to incur deficits of 0.6–16.7 billion USD in 2035. Current and future oil dependence for Ecuador would increase vulnerability and compromise the country in terms of energy security and trade balance. It is critical for Ecuador to consider more ambitious policies focused on energy efficiency, renewables and diversification of the productive structure over the next few years.

1. Introduction

Due to its widespread use, oil is considered one of the most relevant energy sources worldwide [1]. Estimating the maximum extraction (i.e. peak) of finite sources, and specifically oil, has been the center of attention given its importance [2], and the sharp increase in its consumption during the 20th century [3]. Even though “Peak-Oil” as a concept has its roots in the early 2000s, the question of for how long its extraction and use can be continued under current conditions has been the object of multiple studies. One of the key works that triggered many of the peak oil research studies over the past 20 years is Campbell and Laherrère's “The End of Cheap Oil” [4]. In this paper, authors forecasted that global oil extraction might well begin to decline within the following 10 years. However, rather than predictions, the results are maximum extraction profiles that only use geological constraints and might be affected by such variables as geopolitics, economic conditions, and technology development [2,5–8].

In 1956, M.K. Hubbert stated that the cumulative oil extraction in the United States could be modeled using a logistic function [6,9]. The first derivative of this function takes a probabilistic bell shape representing the yearly extraction, which allows the point of time at which the extraction reaches its peak and starts to decline due to geological constraints [7]. One of the parameters of this forecast was the ultimate recoverable resources (URR), which is the amount of resources that are anticipated to be recovered from a country, region, or field from when extraction begins to the end of the extraction process [10].

The Hubbert model has been extensively used to model the extraction of hydrocarbons and minerals. Studies cover from worldwide oil extraction forecast [5] to regional and national

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Nomenclature

Abbreviations

URR	Ultimate Recoverable Resources
MMbbl	Million Barrels
MMbbl/d	Million barrels per day
USD	United States Dollar
Bpd	Barrels per day
Cv	Coefficient of variation
SOTE	Trans-Ecuadorian Oil Pipeline System
OCP	Heavy Oil Pipeline
EOR	Enhanced Oil Recovery
ITT	Ishpingo-Tambococha-Tiputini
BAU	Business As Usual
ALT	Alternative
2P	Proved + Probable reserves
O	Optimistic
IEA	International Energy Agency
WEO	World Energy Outlook
OPEC	Organization of the Petroleum Exporting Countries
US EIA	United Stated Energy Information Administration

Symbols

P	Oil extraction (MMbbl)
P_{pk}	Oil Peak extraction (MMbbl)
T_{pk}	Time corresponding to peak extraction (years)
t	Time (years)
b	Constant
k	Constant
$g(t)$	Sigmoid function adjusting the standard deviation at the time of the peak extraction

Greek symbols

σ	Standard deviation

Subscripts

inc	Increasing side of the curve
dec	Decreasing side of the curve
i	Number of extraction cycle
N	Total extraction cycles

approaches, such as the cases of OPEC countries [11], Peru [12], Brazil [13,14] or China [15], among others. The use of Hubbert approach for modeling extraction beyond conventional oil, can be found in such cases as nonconventional oil [16,17], natural gas and coal [5,18–22], phosphorus [23], precious metals [24], or aluminum and copper [25]. Even though the fit achieved with the original Hubbert method has been useful to forecast extraction in some cases, in others, results have shown sharper extraction peaks than suggested by the Hubbert curve [26]. This method has been criticized most of all because of its lack of any adequate theoretical basis, for using empirical data, and for relying on assumptions regarding the URR which could be uncertain, for its sensitivity related to the selection of a functional form, and for disregarding the effects of economic and political variables [27].

By analyzing the oil extraction patterns of the major producing regions and countries worldwide, Brandt found that the majority of extraction sets had a better fit with asymmetric curves as opposed to the standard symmetric Hubbert [26]. Similar objections to the use of the original Hubbert method have been stated by Bardi [28], Mohr [29], and Nashawi [30].

The disruptions attributed to variables apart from geology can manifest themselves with the emergence of different extraction cycles [31]. Furthermore, these factors might generate a range of possible shapes for extraction cycles and uncertainty regarding the time when peaks in extraction would be reached [27]. An alternative method that addresses these criticisms is the use of Multiple Hubbert curves. This approach allows extraction cycles, which are dependent on the expected resource benefits in each cycle to be modeled [12]. Because of this characteristic, it has been consistently used in the modeling of oil extraction [5,11–13,30,32–36].

Likewise, other methods apart from Hubbert have been developed. Laherrère [34] proposed a variant of the Hubbert model by adding another parameter to the “classic” curve. The Hubbert Linearization model is used to determine the URR, which is a parameter of the Hubbert Model [37,38]. The Generalized-Weng and the multicyclic-Generalized-Weng models described by Chen [39] have been extensively applied to forecast oil [35], natural gas [40] and rare earth metals extraction in China [41]. Mohr proposed a model initially used for coal extraction [42] which was later applied to unconventional oil [43], conventional oil, and natural gas [44]. It was determined that oil, natural gas and coal extraction ramp up in one year to maximum extraction and a plateau, followed by an exponential smooth decline [44]. This model has presented a good fit for the extraction profile of giant oil fields.

Oil in Ecuador is currently extracted in the Amazonian territories (Oriente Basin) and the coastal region of Santa Elena (Santa Elena Sub Basin). The Oriente basin holds a sedimentary Paleozoic fill up to a recent age. The most interesting section is limited to the deposition cycle from the Cretaceous, and all the significant extraction comes from the fluvial and marine sandstones in the Hollin and Napo formations [45]. These two formations contain the main reservoirs: Hollin, T, U, and M1. The Tena Basal reservoir, as well as the A, B and M2 are considered marginal pools [46].

The Hollin reservoir gets its maximum development at the south-western region of the basin and at the south near the Marañon basin. Meanwhile, the Lower T and Lower U reservoirs exhibit the best petro physical characteristics associated to fluvial and estuary facies at the south-east and east of the basin, respectively. The upper T and U bodies, with poorer properties as reservoirs than their lower bodies, develop toward the superior stage of the stratigraphic section. Finally, the sandstone M1 is a reservoir that, in contrast to the T and U pools, is restricted to the eastern zone of the basin.

According to Baby [47], at the north and middle of the Oriente basin there are at least three different petroleum plays, each with its proper characteristics. The Occidental play, adjacent to the Andes mountain range, is characterized by the dominance of the lower Hollin reservoir, with 98% of the oil in situ. This play contains the prospective Pungarayacu field, which concentrates the greatest oil accumulation in the area and an estimated 16% of the oil in the basin.

The Central play is the largest one and holds the greatest reserves of light oil, with a predominance of U reservoir (±35% of the reserves), lower Hollin (±29%), and T (±26%), with a predominance of estuary facies. The play contains the fields Shushufindi and Sacha, with an estimated 54% of the oil in situ of the basin.

Finally, the Oriental play holds 30% of the basin oil in situ, concentrated in the M1 sandstone with approximately 59% of the oil in the play and the U sandstone with 28%. The largest reservoir is the field Ishpingo, with a preponderance of heavy oil reserves.

Oil extraction in Ecuador started in 1878 in Santa Elena. In 1967, the first oil well in the Amazonian region was drilled, and in 1969, Shushufindi - Aguarico and Sacha fields were discovered, with 1600 and 1200 million barrels (MMbbl) in proved reserves, respectively [48]. In 1972, Ecuador attained for the first time the status of net oil exporter, with oil exports reaching 24.9 (MMbbl) that year. This achievement was greatly boosted by the inauguration of the Trans-Ecuadorian Oil Pipeline System (SOTE) [49], which started with a capacity of 250,000 barrels per day (bpd) and is still in operation, with an increased capacity of 360,000 bpd [50]. In 1980, Libertador field was discovered, becoming the third largest field in the country with approximate proved reserves of 430 MMbbl [48].

Oil extraction suffered a setback in 1987, due to an earthquake that caused considerable damage to the SOTE infrastructure, stopping oil extraction for about six months [51]. Annual extraction went from 105 MMbbl in 1986 to 63 MMbbl in 1987 [48]. Oil extraction continued to grow until 1997, when it reached a new peak of 141 MMbbl. In 2003, the Heavy Oil Pipeline (OCP) was inaugurated. With a capacity of 450,000 bpd, it allowed the repressed extraction to find a way out towards the exporting ports. With the construction of the OCP, a new extraction cycle started for Ecuador, with annual extraction going from 142 MMbbl in 2002 to 192 MMbbl in 2004 [52].

In 2012, the government invested 1362 million Dollars in the oil industry, an increase of 21% with respect to 2011. The government started in 2012 an Enhanced Oil Recovery (EOR) program in six of the largest fields of the country: Paca-Sur, Eden-Yuturi, Lobo, Oso, Sacha, and Shushufindi. According to Petroamazonas, the average recovery using water injection was 24% in the first years of application, with cases like Shushufindi increasing its extraction from 16 to 27 MMbbl between 2012 and 2015, and partially reverting its falling extraction profile (See Supplementary Data D) [53].

In 2014, oil extraction in Ecuador reached its historic maximum to date with 203 MMbbl [48] In 2015 it declined to 198 MMbbl, with a daily extraction of 543 thousand barrels (Fig. 1, Bottom), considering an average of 5974 wells drilled. The largest contribution of oil extraction corresponds to the fields: Sacha, Shushufindi, Auca, Eden-Yuturi, Oso, Aguarico, Cuyabeno, Palo Azul, Fanny 18-B and Villano, which together represent 53.53% of the total extraction [54] (see Supplementary Data A).

According to OPEC and the US EIA, by the end of 2016, Ecuador had 8.3 billion barrels in proved reserves (extracted + remaining) [55,56], most of which is medium crude oil (Fig. 1, Top). The Orient Basin contains over 97% of the current proved reserves [50,55]. Ecuadorian oil exports are currently made up of two types of oil: Orient, with an average of 26° API, and the semi-heavy Napo, of 19° API on average [48]. Based on historical data, Ecuador has currently exploited 63% of its reserves, leaving only 37% to be exploited, most of which are medium oil. However, the Secretary of Hydrocarbons in 2018 published a report updating the proved reserves to 7.5 billion barrels (extracted + remaining) [57] and uses the concept of "Estimated Ultimate Recovery" to represent this sum.

In 2015, 88% of primary energy extraction in Ecuador was made up of oil. Of this extraction, 23% goes to internal use (approximately 48.5 MMbbl are destined for the refining process, 1.8 million for self-extraction power plants, and 0.751 million for own use in pipeline transport), while 65% goes to export [52].

According to field size classification proposed by ENI [58], 42% of oil reserves in Ecuador are part of large fields, 33% of giant fields, 22% of medium fields and 3% of small fields. At the beginning of the oil era in Ecuador, giant fields such as Sacha and Shushufindi-Aguarico covered around 78% of total extraction. After 1998 there was a notable decline in the extraction of these fields, covering only 33% of national extraction, as they entered their period of maturity (Fig. 1 bottom).

In 2015 oil sales represented 34% of the total exports (6355 Million FOB USD) [52,59,60]. Oil revenues from 2006 to 2017 have represented on average 23% of total revenues, reaching values above 30% in the period 2010–2012, supported by high oil prices [61]. Furthermore, oil exports accounted for 48% on average of total exports during the last decade, also reaching the highest values from 2010 to 2012 [62].

Given the importance as a source of income for the country, it is critical for future planning to make robust projections about oil extraction. Models for certain countries in the region have usually relied on symmetrical Hubbert [11–13]. Studies for Ecuador have been based on the Symmetric-Hubbert [63,64], and the Symmetric-Multi-Hubbert approach [11]. The first two analyses found that peak year would be reached in 2009 and 2006, respectively, based on URR values of 8 billion barrels in Ref. [63] and 9 billion barrels in Ref. [64]. The third study reported that peak year might be reached in 2007 based on a URR of 10.7 billion barrels. The historical year of maximum extraction and profiles developed for Ecuador previously show a gap of around five to eight years. While different oil extraction models can be used considering the national or regional scale, only one approach has been used to assess Ecuador. In this sense, it is of interest to use another approach to develop a more robust forecast. This work aims to expand this type of analyses by including an asymmetrical model, for both single and multi-Hubbert cases, to evaluate the Ecuadorian instance. Furthermore, the studies described above use total national data for fitting purposes only, or at most the data from two or three large regions. In the same way that extraction profiles between countries differ, oil fields in the same country can display different characteristics and extraction figures. Based on references, Miller and Sorrell suggested that modeling the extraction of individual fields and constructing national, regional or global forecasts (bottom-up) is a more propitious approach [27]. Hence, the present paper additionally introduces a bottom-up approach, in which the models of all the individual oil blocks in Ecuador add up to constitute the total national forecast.

The top-down and bottom-up approaches are compared to identify the differences regarding: goodness of fit, maximum extraction, and peak year. An analysis of the oil extraction forecast, and the national oil demand is carried out considering two scenarios: Business as Usual (BAU), and Alternative (ALT). Finally, based on the results, the oil revenue projection is estimated according to future price projections from the IEA [65]. The results obtained are relevant for future planning of this natural resource in Ecuador.

The methodology used to model oil extraction is explained in section 2, Section 3 has a summary of the results obtained. Discussion about these results is included in Section 4, and Conclusions in Section 5.

2. Methodology

Hubbert used the logistic function to calibrate empirical data and define the behavior of the cumulative extraction in an oil well. When the first derivative of this function is taken, a function that graphs a bell-shaped curve representing the yearly extraction is obtained. A common way to represent this function is proposed by Maggio and Cacciola [5]:

$$P = \left(2P_{pk} \Big/ \left(1 + k\cosh\left[b\left(t - T_{pk} \right) \right] \right) \right) \quad 0 < \mathrm{k} \leq 1 \tag{1}$$

where P represents the extraction at time t, P_{pk} is the peak extraction, T_{pk} is the corresponding peak time, b is a constant that

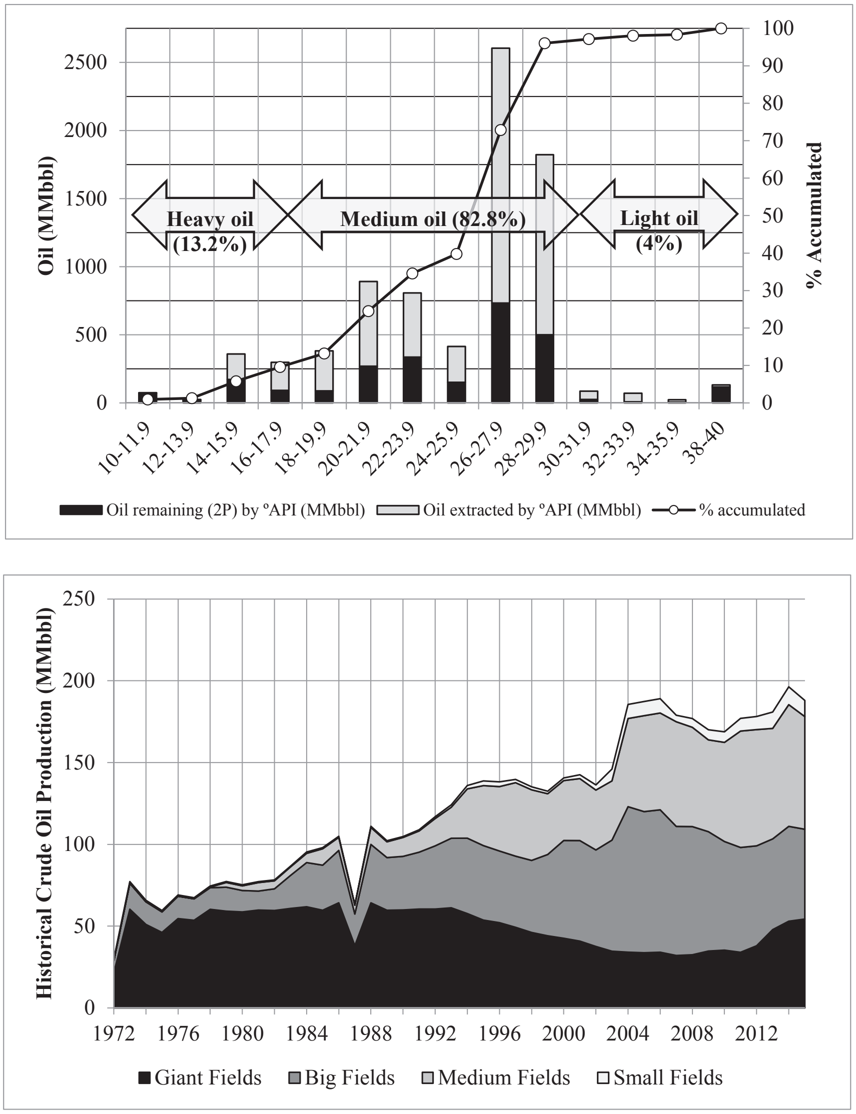

Fig. 1. (Top) remaining oil reserves and extracted by °API in Ecuador. (Bottom) Historical crude oil extraction by field size in Ecuador.

determines the curve slope, and k is an adjusting constant set to 1 in order to reduce the parameters from four to three.

The use of the Multi-Hubbert approach is oriented towards including in the extraction profiles disruptions caused by implementation of new technology, government policies and economic changes. These factors might cause several cycles over the extraction period of a country, and often are not represented by a regular single-peak Hubbert method.

The Multi-Hubbert model is defined as the sum of the different Single-Hubbert cycles over the total extraction life (Eq. (2)).

$$P=\sum_{i=1}^{N}\left(2P_{pki}\Big/\left(1+k\cosh\left[b_i\left(t-T_{pki}\right)\right]\right)\right)\qquad 0<k\leq 1 \tag{2}$$

The asymmetric case was modeled based on the work of Brandt et al. [26]. It uses a Gaussian curve as base, with the ability to include different standard deviations on the increasing and decreasing sides. It works as a compound function of the form:

$$P=P_{pk}\bullet\exp\left(-\left(t-T_{pk}\right)^2\Big/2g(t)^2\right) \tag{3}$$

where, $g(t)$ is the sigmoid function adjusting the standard deviation at the time of peak extraction.

$$g(t)=\sigma_{dec}-\left(\left(\sigma_{dec}-\sigma_{inc}\right)\Big/\left(1+\exp\left(k\left(t-T_{pk}\right)\right)\right)\right) \tag{4}$$

where P represents the extraction at time t, P_{pk} is the peak extraction, T_{pk} is the corresponding peak time, σ_{dec}, and σ_{inc} are, respectively, the decreasing and increasing side standard deviations, and k is the rate of change between standard deviations. As in the previous case, the multiple-peak model is obtained through the summation of the single cases of each extraction cycle:

$$P = \sum_{i=1}^{N} \left(P_{pki} \bullet \exp\left(-\left(t - T_{pki}\right)^{2} \Big/ 2g_{i}(t)^{2} \right) \right) \tag{5}$$

with

$$g_{i}(t) = \sigma_{deci} - \left(\left(\sigma_{deci} - \sigma_{inci}\right) \Big/ \left(1 + \exp\left(k\left(t - T_{pki}\right)\right)\right) \right) \tag{6}$$

Oil extraction dataset used in the present work was taken from the statistical report issued by Petroecuador [50]. It includes the daily extraction of each producing field converted to yearly amounts to keep the same format as the national data. Additionally, the information about reserves and resources were obtained from the Yearly Report of Ecuadorian Hydrocarbon Potential [57]. Hubbert approach was evaluated in both a national-aggregated and a by-block basis (a block is a set of oil producing fields as defined by the Ecuadorian Secretary of Hydrocarbons for oil extraction contract awarding). The study performed with block information corresponds to the superposition of the modeled extraction of each block.

Two URR cases were considered. The first, known as *2P*, establishes the URR by adding the cumulative extraction to the summation of proved and probable (2P) reserves [57]; the URR used for this case was named URR(2P). Thus, this case corresponds with a level of oil endowments currently estimated to be economically profitable with a 50% probability. The second case, named *Optimistic*, defines the URR as the sum of cumulative produced oil, proved, probable and possible reserves, contingent resources and prospective (yet-to-find) resources; this URR was named URR(O). Thus, URR(2P) considers reserves which are known to be exploitable with a reasonable level of uncertainty (as considered by Ref. [66]); while URR(O) includes endowments with a high degree of uncertainty and represents a more speculative scenario based on currently available information. The information on URR for both scenarios in the national case is depicted in Table 1.

URR has also been estimated in this work using Hubbert Linearization, which allows the long-term total extraction of an oil or gas field to be estimated from current data. It uses a graphical approach to plot the behavior of extraction from a field, with the main assumption (or hypothesis) being that URR can be derived from the X intercept of an extrapolation of the plot of the ratio of annual extraction to cumulative extraction (Y axis) versus the cumulative extraction (X axis) [37,38]. Fig. 2 shows the results of applying this method, resulting in a URR of 9562 MMbbl, a value within the range of the 2 cases considered.

For the bottom-up approach, a total of 25 blocks were defined from the data in Ref. [57], (see Supplementary Data C). Definitions applied for the national case are also considered for each block. Therefore, URR(2P) in this case corresponds to the sum of the cumulative extraction and 2P reserves of each block. To consider the possible reserves, contingent resources and prospective resources (URR(O)) in the bottom-up approach, an additional block is defined adding them. This block was modeled using both symmetrical and asymmetrical single-peak models and added to the rest of the block models for the bottom-up approach in URR(O).

Table 1
Cases and URR for the Top-Down approach.

Top-Down Approach	Nomenclature	URR (MMbbl)
2P Case	URR(2P)	7854
Optimistic Case	URR(O)	10,683

The proposed additional block is not currently under extraction, so there is no historic data available to estimate whether there will be a second cycle or when it would occur. This led to a representation with only single-cycle models. The parameters taken for modeling this block are the same as those of the Shushufindi-Aguarico block, as both contain a similar amount of reserves. After building the bottom-up model for the total extraction of the country, the parameters for each of the cases were found using the code to find the best-fit curve.

Oil extraction in the additional block is assumed in this work to start in 2022, to supply in part a new planned refinery complex with an estimated input capacity of 300,000 bpd that would start to operate in the same year. The *Optimistic Case* adds this block to the ones in the *2P Case*, obtaining the URR(O).

The information on the hydrocarbon potential provided in Ref. [57] contains the reports of reserves available up to December 31st, 2016. Some prospects, such as the fields of Curaray, Danta and Pugarayacu, are still being evaluated and are not included in the report. Their positive assessment could increase the country's final URR. However, this work keeps the URR based on the available official information [57].

For each of the cases, the Symmetric and Asymmetric Hubbert Models, in both the single and multi-Hubbert variants, were simulated in MATLAB from 1972, the first year with significant oil extraction, to 2100.

In the case of the Multi-Hubbert models, one of the requirements was to provide a guess for the start of the second cycle. A major growth in extraction occurred between 2003 and 2004 due to the start of operation of OCP pipeline. Hence, 2004 was entered as the guess for modeling a second cycle. In the same way, each block was assessed to determine its suitability for a Multi-Hubbert approach.

For the symmetric estimation, the parameter b was allowed to vary between 0 and 1, and the remaining parameters were found by the MATLAB optimal estimator function *fminsearch* with the URR as constraint. The same method was used with the asymmetric case but varying the value of σ_dec between 0 and 50. To test the selected variable parameters against the returned URR, both symmetric and asymmetric Hubbert functions were simulated, with the Ecuadorian historical extraction as input data, and parameters b and σ_dec varying in steps of 0.1. The resulting URR values were plotted as shown in Fig. 3, indicating that up to the maximum potential URR (10,702 MMbbl), a specific parameter value is corresponded by a single URR value, and thence the same URR value will not be obtained with different values for the same parameter.

In the asymmetric case, guess estimates of the declining rate are entered for the estimation and are set to 5%, according to the findings by Höök in Ref. [67], which determined that even though the average decline rate for land-based fields in OPEC countries is 3.8%, it has evolved to reach 9.8% in the 2000s for giant fields, which usually enclose a large proportion of the extraction and reserves of a country. A total of 16 scenarios are tested (4 variables with 2 options each) (see Table 2):

3. Results

Fig. 4 shows the results of the different Hubbert models considered for the URR(2P) and URR(O) cases for the national approach. In the URR(2P), the symmetric single-peak model advances peak extraction to 2007, while the other models delay it to 2014–2016, which corresponds with the maximum annual extraction from the historic time series in 2014. For the optimistic case, URR(O), the asymmetric single-peak model is the only projection that delays the absolute maximum extraction to 2025, while the other models also position it in the range 2013–2016. By 2040,

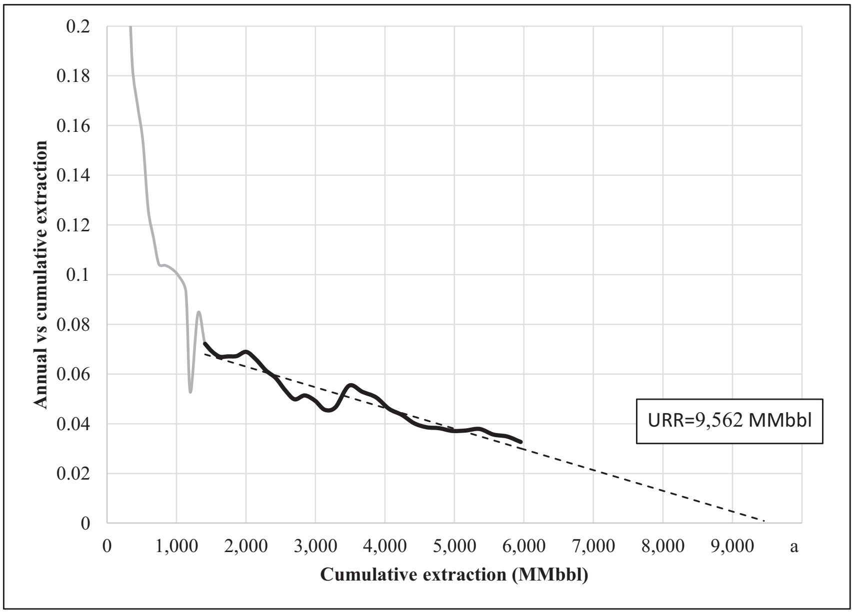

Fig. 2. Application of Hubbert Linearization for the Ecuadorian case. Linear extrapolation for the period 1989–2017.

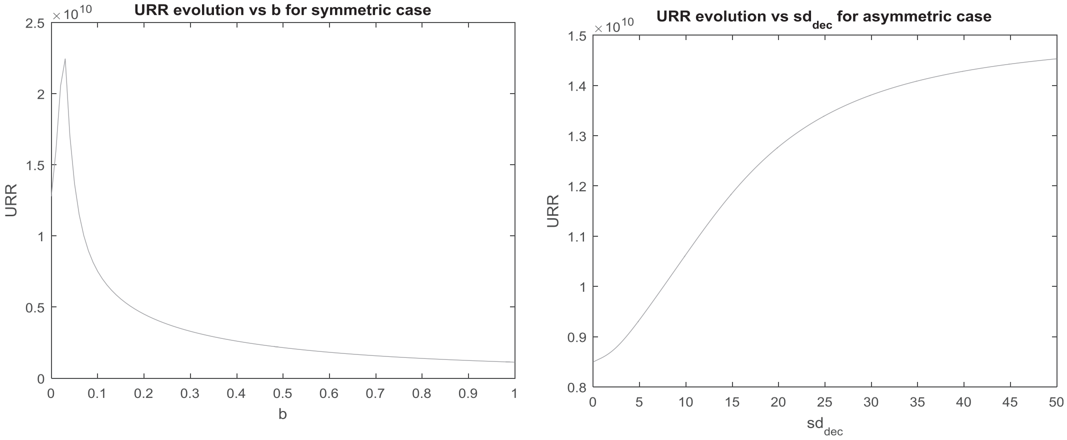

Fig. 3. (left): URR evolution with respect to *b* for symmetric case, (right): URR evolution with respect to *σ_dec* for the asymmetric case.

Table 2
Variables and options for scenario design.

Approach	Hubbert Model	Cycles	URR
National: (N) Top-down	Symmetric (Sym)	Single cycle (S)	URR(2P)
Blocks: (B) Bottom-up	Asymmetric (Asym)	Multi-cycle (M)	URR(O)

all models have an annual extraction of 0–50% of current extraction levels.

Fig. 5 shows the results of the different Hubbert models considered for URR (2P) and URR(O) cases for the blocks approach. The blocks approach single-peak curves, independently of the model used (symmetric or asymmetric), advance the maximum extraction to the years 2005 and 2007, in both URR cases. The multi-cycle models delay this peak to 2017 in all cases, which is more in accordance with historical data.

In the case of URR(2P), the year at which extraction comes down to half current value (100 MMbbl) for the national approach models (Fig. 4) is in the range 2025–2027, whereas the blocks approach models (Fig. 5a) advance it to 2023–2025. When URR(O) is considered, the national approach brings the 100 MMbbl extraction year to 2038–2040, while the blocks approach advances it to 2025–2030 (Fig. 5b). These results show the main differences between approaches. The introduction in the bottom-up approach of a block that contains possible reserves, contingent resources and prospective resources, in the optimistic case, results in an earlier decay of oil extraction (from 2017 to 2027) and then a smoother decline profile as compared to the national approach from 2027 onwards (see Fig. 5b). Under a national approach, this is not possible, because these remaining resources are all integrated under the curve and cannot be introduced in any given year. Bottom-up models allow blocks to be introduced based on planned future requirements.

Detailed results of the estimated parameters for each model and case are presented in Tables 3 and 4. In relation to the goodness of fit, the coefficient of variation (Cv) has the lowest values in both approaches when multi-cycle is considered, independently of the Hubbert model (symmetric and asymmetric), lying within a short range (from 5.1% to 5.7%). Moreover, the models within this range of Cv present peak years close to the historical maximum extraction.

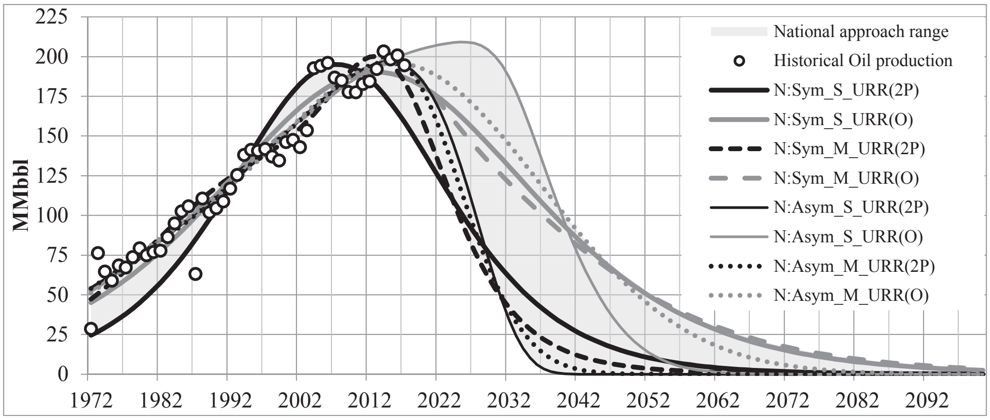

Fig. 4. Ecuadorian oil extraction forecast from national approach (N, Top-down approach) for Symmetric (Sym) and Asymmetric (Asym) Hubbert model, with a single-cycle (S) or multiple cycles (M). Black lines refer to URR = 7.8 MMbbl (2P) and grey lines for the optimistic case, where URR = 10.7 MMbbl (O). The shadowed area represents the range of results from the different models and assumptions considered.

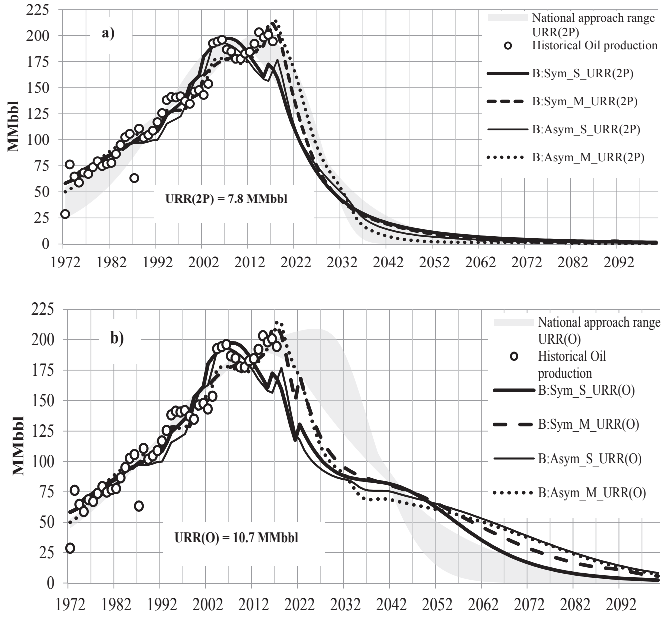

Fig. 5. a): Ecuadorian oil extraction forecast from Blocks approach (B, Bottom-up approach) for Symmetric (Sym) and Asymmetric (Asym) Hubbert model, with a single-cycle (S) or multiple cycles (M). URR(2P) = 7.8 MMbbl. The shadowed area represents the range of results from the different models and assumptions considered for the national approach (N). b): Ecuadorian oil extraction forecast from Blocks approach (B, Bottom-up approach) for Symmetric (Sym) and Asymmetric (Asym) Hubbert model, with a single-cycle (S) or multiple cycles (M). URR(O) = 10.7 MMbbl. The shadowed area represents the range of results from the different models and assumptions considered for the national approach (N).

However, the national symmetric multi-cycle model gave a value closer to the historical maximum extraction. Based on the fit to historical data and peak year criteria in the 2P case, the symmetric single-cycle would not be suitable for the top-down approach, whereas the symmetric and the asymmetric single-cycle could be discarded. Multi-cycle models presented Cv values of around 5%, which reinforces the accuracy of the assumption regarding the start of the second cycle.

URR(O) case, as presented in Table 4, shows that multi-cycle models, symmetric and asymmetric in both approaches, show the best fit to historical data in terms of Cv, which lies within an even shorter range as compared to the 2P case (5.0%–5.7%). According to this criterion, the symmetric single-cycle for the national approach, and the symmetric and asymmetric single-cycle for the blocks approach would be disregarded.

Furthermore, peak year range is reduced to 2016–2017. The case of the asymmetric-single-cycle Hubbert under the national approach is different as compared to the rest of the models developed (See Fig. 4). It presents a maximum extraction value in 2025. This may be because there is not enough historical data and the adjustment of the model does not clearly identify the peak and decrease in oil extraction. In this way, the national-asymmetric single-cycle model does not seem realistic due to the rapid decrease in extraction that the model describes.

Regarding the year of 50% peak extraction, the National approach presents a longer delay in URR(O) case as compared to URR(2P) (12–14 years) than the Blocks approach (1 year–8 years). This is due to the new block considered in the bottom-up approach in the URR(O) case, which produces a shoulder in the graph (see Fig. 5b) after the 50% peak extraction is reached.

Statistical significance of the parameters used in the nonlinear symmetric and asymmetric models was determined by evaluating the 95% confidence intervals of the estimated parameters. The evaluation was carried out using the MATLAB built-in function *nlparci*. Results are presented in Tables 5–8.

It can be noted that the parameter sd_dec1 for one cycle is extremely wide, implying that could be considered not significant. As the fitted data lacks enough historic values in the falling side of the curve, the uncertainty of the parameter determining the falling slope of the curve could be large. However, caution should be exercised before rejecting the parameter, as it allows the model to reach the estimated URR closest to the ones provided as constraint.

4. Discussion

For Multi-Hubbert models in the URR(2P) case, the falling sides of the curves under the national and blocks approaches show no noticeable differences. In contrast, the Multi-Hubbert models for the optimistic case present marked differences between them, since the bottom-up approach considers the timing of the operation start-up for the fields that have not started producing, showing a “shoulder” after 2020. Whereas in the case of the national approaches, these integrate the remaining extraction under the whole curve. An observation regarding this fact is that, even though the bottom-up approach requires a larger amount of information than the top-down approach, it can incorporate the start of operations

Table 3
Obtained parameters: URR(2P).

	URR(2P)							
	National				*Blocks*			
	Symmetric		*Asymmetric*		*Symmetric*		*Asymmetric*	
	1 cycle	*2 cycles*	*1 cycle*	*2 cycles*	*1 cycle*	*2 cycles*	*1 cycle*	*2 cycles*
B	0.096	0.09			0.091	0.08		
K	1	1	1	1	1	1	1	1
b2		0.17				0.26		
k2		1		1		1		1
σ_inc1			31.9	13.9			24.2	10.51
σ_dec1			0.6	12.0			12.2	8.76
σ_inc2				19.3				19.27
σ_dec2				9.1				9.04
Peak oil year	2007	2015	2014	2016	2007	2017	2005	2017
Peak oil extraction (MMbbl)	195.0	200.3	196.8	196.4	197.3	211.4	193.6	215.0
URR (MMbbl)	7860.8	7824.3	7889.2	7863.4	7877.1	7911.5	7636.9	7947.1
Cv	11.6%	6.1%	5.1%	5.1%	7.23%	5.57%	8.41%	5.65%
Year of 50% oil extraction	2026	2025	2027	2026	2023	2024	2023	2026
Year of 100 MMbbl extraction	2025	2025	2027	2026	2023	2024	2023	2025

Table 4
Obtained parameters: Optimistic case.

	URR(O)							
	National				*Blocks*			
	Symmetric		*Asymmetric*		*Symmetric*		*Asymmetric*	
	1 cycle	*2 cycles*	*1 cycle*	*2 cycles*	*1 cycle*	*2 cycles*	*1 cycle*	*2 cycles*
B	0.066	0.24			0.056	0.18		
kσ	1	1	1	1	1	1	1	1
b2		0.06				0.04		
k2		1		1		1		1
σ_inc1			31.9	18.2			20.5	17.8
σ_dec1			12.1	3.4			36.3	6.6
σ_inc2				6.9				8.1
σ_dec2				27.5				32.3
Peak oil year	2013	2016	2025	2016	2007	2017	2005	2017
Peak oil extraction (MMbbl)	190.3	197.2	209.1	195.8	197.3	211.4	193.6	215.0
URR (MMbbl)	10,765.9	10,741.8	10,688.7	10,766.8	10,732.6	10,766.1	10,474.2	10,784.2
Cv	6.1%	5.5%	5.1%	5.0%	7.23%	5.57%	8.41%	5.65%
Year of 50% oil extraction	2040	2037	2039	2040	2031	2029	2026	2027
Year of 100 MMbbl extraction	2038	2037	2040	2040	2030	2030	2025	2029

and peak time of the producing blocks in the total curve, resulting in differences like the one stated above. The inclusion of a bottom-up analysis provides greater flexibility, given its modularity and concreteness [68]. This has been suggested as an alternative for better accuracy in near term projections by other works, such as those of Peru [12] and Brazil [13,14].

In the case of Ecuador, detailed field information (in this case blocks) for the use of a bottom-up approach has not been a limitation. Assumptions necessary for this kind of analysis have been focused on decline rates. One particularity of important blocks (Shushufindi-Aguarico and Sacha), due to their size, is the presence of a new extraction cycle attributed to EOR.

In URR(2P) case, the bottom-up models developed can bring good insights regarding short-term projections, given that it is the sum of individual blocks. Moreover, it gives the opportunity to develop such analysis as the effect of implementing EOR techniques, which supports the conclusions of Brandt [7,69]. However, the additional block defined for bottom-up modeling, under URR(O) case, assumes a similar behavior to the largest block in the country based on their similar size. These considerations bring uncertainty, given that it is not known whether this block would follow the same behavior pattern as blocks that started up 20 or 30 years ago. As seen in the literature [67,70], the decline rate for new fields tend to be higher than in the past, given that new extraction technologies allow prolonged plateaus that cause a subsequent pronounced decline. Furthermore, the influence of other factors, apart from geology, might produce future cycles that cannot be identified today. Additional peaks might occur in the future due to technology, policy changes, or oil prices creating a new extraction cycle.

For URR(2P) case, when considering the national approach, asymmetric models (single or multi-peak) identify better the peak extraction year and have a lower Cv. In the blocks approach, the multi-peak models (symmetric or asymmetric) show a better Cv and identification of peak extraction. Other studies developed [12,13] have proved that multi-peak models present a better fit for historical data. Accordingly, the results obtained in this work support this remark for both approaches and models used (symmetric and asymmetric). Therefore, top-down approaches should use asymmetric models, while bottom-up approaches should use multi-peak models.

In URR(2P), the average yearly declining rate for the asymmetric model is around 7%, which is greater than the 3% average yearly growth rate and is close to the average worldwide extraction decline rate estimated by the IEA in 2016 (6.2%) [71]. Brandt [26] favors asymmetrical models with declining rates lower than

Table 5
Statistical significance of parameters obtained for Hubbert Models URR(2P) Top Down Approach.

	URR(2P)							
	National							
	Symmetric				*Asymmetric*			
	1 cycle		*2 cycles*		*1 cycle*		*2 cycles*	
Parameter	*Estimated value*	*Confidence Interval*	*Estimated value*	*Confidence Interval*	*Estimated value*	*Confidence Interval*	*Estimated value*	*Confidence Interval*
B	0.09	[0.08–0.11]	0.09	[0.04–0.14]				
K	1	[1–1]	1	[1–1]	1	[1–1]	1	[1–1]
b2			0.17	[0.04–0.30]				
k2			1	[1–1]			1	[1–1]
σ_inc1					31.9	[25.2–38.8]	13.9	[-19.5 - 47.3]
σ_dec1					0.6	[-214,076.8 −214,078.0]	12.0	[-27.7 - 51.8]
σ_inc2							19.3	[-21.9 - 60.5]
σ_dec2							9.1	[-214.1 - 232.3]
Peak oil year	2007		2015		2014		2016	
Peak oil extraction (MMbbl)	195.0		200.3		196.8		196.4	
URR (MMbbl)	7860.8		7824.3		7889.2		7863.4	
Cv	11.6%		6.1%		5.1%		5.1%	
Year of 50% oil extraction	2026		2025		2027		2026	
Year of 100 MMbbl extraction	2025		2025		2027		2026	

*95% confidence interval.

Table 6
Statistical significance of parameters obtained for Hubbert Models URR(2P) Bottom Up Approach.

	URR(2P)			
	Blocks			
	Symmetric		*Asymmetric*	
	1 cycle	*2 cycles*	*1 cycle*	*2 cycles*
Parameter	*Estimated value*	*Estimated value*	*Estimated value*	*Estimated value*
B	0.091	0.08		
K	1	1	1	1
b2		0.26		
k2		1		1
σ_inc1			24.2	10.51
σ_dec1			12.2	8.76
σ_inc2				19.27
σ_dec2				9.04
Peak oil year	2007	2017	2005	2017
Peak oil extraction (MMbbl)	197.3	211.4	193.6	215.0
URR (MMbbl)	7877.1	7911.5	7636.9	7947.1
Cv	7.23%	5.57%	8.41%	5.65%
Year of 50% oil extraction	2023	2024	2023	2026
Year of 100 MMbbl extraction	2023	2024	2023	2025

*Estimated parameters correspond to weighted average of the values for each field; hence no confidence intervals are presented.

growth rates, but this is not relevant for the Ecuadorian 2P case because the cumulative historic extraction exceeds half the reserves. This also supports the assumption of Bardi [28], where declining extraction rates could be greater than the rates of increase. Hence, the asymmetric analysis in the 2P case is represented by a negative-skewed curve, meaning that oil extraction in Ecuador could rapidly decline after peak, showing agreement with results obtained by Wang [72]. It therefore shows that, within a range between 2023 and 2027, peak extraction in Ecuador will decline in 50%.

Single-cycle models tend to advance the year of peak extraction, which is in agreement with Ebrahimi's estimation [11] in terms of peak time (2006) and extraction (195.9 MMbbl). However, historical data have shown that the maximum extraction so far in Ecuador was not reached in that year. Hence, the inclusion of a thorough socio-historic analysis can be useful to spot the appearance of extraction cycles and see how they influence the shape of the model. Clear examples of the effects of factors apart from geology are: a) the increase in oil extraction from 2003 to 2004, which is attributed to the start of operation of the heavy oil pipeline: b) the decline registered from 2007 to 2010 due to the world economic crisis, and c) the extraction increment related to the issuance of the Reforming Law of Hydrocarbons, which changed the status of all the private companies to service providers, with the state receiving all the oil produced, and an increase of government investment in the oil industry.

Laherrère, in his work in 2008 for Ecuador, modeled a cumulative discovery curve with a final value of around 9000 MMbbl [64]. This is a small increase compared to the cumulative discoveries registered up to 2007 (8200 MMbbl). As remarked by Sorrell [73], the discovery of large fields tends to take place in the early stages of exploration. In the case of Ecuador, the largest blocks (Shushufindi-

Table 7
Statistical significance of parameters obtained for Hubbert Models URR(O) Top Down Approach.

	URR(O)							
	National							
	Symmetric				*Asymmetric*			
	1 cycle		*2 cycles*		*1 cycle*		*2 cycles*	
Parameter	*Estimated value*	*Confidence Interval*	*Estimated value*	*Confidence Interval*	*Estimated value*	*Confidence Interval*	*Estimated value*	*Confidence Interval*
B	0.066	[0.06–0.07]	0.24	[-1.23 - 0.75]				
K	1	[1–1]	1	[1–1]	1	[1–1]	1	[1–1]
b2			0.06	[0.02–0.10]				
k2			1	[1–1]			1	[1–1]
σ_inc1					31.9	[25.2–38.8]	18.2	[14.9–21.5]
σ_dec1					12.1	[-214,254.1 −214,278.3]	3.4	[2.1–4.7]
σ_inc2							6.9	[5.2–8.6]
σ_dec2							27.5	[4.5–50.5]
Peak oil year	2013		2016		2025		2016	
Peak oil extraction (MMbbl)	190.3		197.2		209.1		195.8	
URR (MMbbl)	10,765.9		10,741.8		10,688.7		10,766.8	
Cv	6.1%		5.5%		5.1%		5.0%	
Year of 50% oil extraction	2040		2037		2039		2040	
Year of 100 MMbbl extraction	2038		2037		2040		2040	

*95% confidence interval.

Table 8
Statistical significance of parameters obtained for Hubbert Models URR(O) Bottom Up Approach.

	URR(O)			
	Blocks			
	Symmetric		*Asymmetric*	
	1 cycle	*2 cycles*	*1 cycle*	*2 cycles*
Parameter	*Estimated value*	*Estimated value*	*Estimated value*	*Estimated value*
B	0.056	0.18		
K	1	1	1	1
b2		0.04		
k2		1		1
σ_inc1			20.5	17.8
σ_dec1			36.3	6.6
σ_inc2				8.1
σ_dec2				32.3
Peak oil year	2007	2017	2005	2017
Peak oil extraction (MMbbl)	197.3	211.4	193.6	215.0
URR (MMbbl)	10,732.6	10,766.1	10,474.2	10,784.2
Cv	7.23%	5.57%	8.41%	5.65%
Year of 50% oil extraction	2031	2029	2026	2027
Year of 100 MMbbl extraction	2030	2030	2025	2029

*Estimated parameters correspond to weighted average of the values for each field; hence no confidence intervals are presented.

Aguarico and Sacha) were discovered in 1969. Regarding (ITT), discoveries were registered in 1970 (Tambococha), 1992 (Ishpingo), and 1993 (Tiputini), respectively [64]. The final value obtained by Laherrère is very close to the URR obtained using Hubbert Linearization (9562 MMbbl) and lies between the two cases considered (2P and O), which reinforces the robustness of the analysis. Following the aim of the work developed by Chavez for Peru [12], the present study has defined boundaries for future oil extraction in Ecuador and is not intended to be used as an accurate prediction.

A comparison of the average daily extraction forecast was performed between the models that presented the best fit to historical data (lowest Cv) and the projections developed by the IEA in its World Energy Outlook (WEO) 2017 [65] for Ecuador under the New Policies Scenario. As depicted in Table 9, it is possible to infer that the WEO considered in its forecast a URR similar to the optimistic case in this work. Of all the models included for URR(O) case, the extraction values for the National-Symmetric-multi-cycle model agree with the WEO.

Not considering the influence of factors such as technology, oil prices, and social, environmental and political issues for the extraction forecast is one of the limitations of the methodology applied in this work. However, those events are difficult to predict in practice, and the methodology used is focused on finding “maximum extraction curves.” The results obtained are a starting point for further analysis such as the effects of implementing EOR techniques, estimating GHG emissions of oil extraction activity or assessing the effects of policies focused on climate change mitigation (reducing Oil consumption and in consequence its extraction), which are out of the scope of the present study.

Technological, and economic variables might also play a key role in the estimation of URR, as their behavior, given the uncertainty, should be described as dynamic and expressed in a probabilistic form, as stated by Sorrell [73]. In February 2017, a national referendum and popular consultation in Ecuador resulted in the support

Table 9
Comparison of average oil extraction forecast for models developed with lowest Cvs and WEO 2017 New Policies Scenario (MMbbl/d).

		URR (2P)				URR (O)				
Year	WEO 2017 New Policies Scenario	National Asymmetric 1 cycle	National Asymmetric 2 cycles	Blocks Symmetric 2 cycles	Blocks Asymmetric 2 cycles	National Symmetric 2 cycles	National Asymmetric 1 cycle	National Asymmetric 2 cycles	Blocks Symmetric 2 cycles	Blocks Asymmetric 2 cycles
2000	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
2016	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.6	0.5
2025	0.4	0.4	0.3	0.2	0.3	0.4	0.6	0.5	0.2	0.4
2030	0.4	0.2	0.2	0.1	0.2	0.4	0.5	0.4	0.1	0.3
2035	0.3	0.03	0.1	0.1	0.1	0.3	0.4	0.4	0.1	0.2
2040	0.3	0.001	0.02	0.1	0.03	0.3	0.3	0.3	0.1	0.2

of limiting the area for oil exploitation in Blocks 31 and 43 (ITT) from 1030–300 ha, while increasing the “Intangible” area of the Yasuni National Park by at least 50,000 ha [74]. However, according to Petroamazonas, this would not result in the reduction of extraction of available reserves and, consequently, the URR [75].

In this sense, another limitation of the current study is the URR considered. Official information available comes from a government body and this could be considered a “political” or “economic” database. In 2016, ITT fields that registered reserves of 920 MMbbl increased to 1670 MMbbl and were certified by Ryder Scott [76]. However, in the report used for this work, only 8.2% of the certified reserves are 2P and the remaining share is possible reserves (28.5%) and contingency resources (63.2%). Furthermore, the Curaray, Danta and Pungarayacu fields have not been considered in the official report of the Secretary of Hydrocarbons [57]. Positive outcomes of the studies of these fields would result in a higher URR. According to information from 2013, proved reserves of these fields consisted of around 360 MMbbl. If these numbers have not changed, their effect on the URR value might not be significant.

An important consideration for future work is that data used in this study and information depicted in Ref. [64] for Ecuadorian giant fields (and consequently the blocks where they are located) show an extraction profile that fits the model developed by Mohr [44]. Considering the increase in extraction that Shushufindi-Aguarico and Sacha have presented (see Supplementary Data B), it is possible that a new extraction cycle might have started. It would therefore be of interest to develop an extraction profile with a bottom-up approach using a combination of Mohr (to describe the first extraction cycle) and Hubbert (to describe the second extraction cycle) models. EOR implementation (see Supplementary Data D) has had different results in all fields used. In the largest fields' extraction increased. Whereas in others, results were not as expected showing a decreasing extraction tendency or a slight reduction on this tendency. This shows that one strategy for reaching the optimistic URR, or at least increase proved reserves in some reservoirs could come from the application of EOR methods in large or giant fields.

Ever since 1972, Ecuador has been a net oil exporter. However, the imports of oil products have increased to satisfy a demand that augments every year. The existing refining infrastructure is limited and has not been expanded since 1977. Refinery outputs are predominantly Heavy Fuel Oil (around 48% on average) followed by Diesel Oil, Gasoline, and Liquified Petroleum Gas (LPG) (52% on average combined). These last three fuels are the most consumed, with a combined share of 67% in 2015 with respect to total consumption. Likewise, the imported share in Diesel Oil, Gasoline, and LPG supply were 69%, 70% and 86%, respectively [52].

To reduce imports of oil products and start progressive exports, the construction of a new refinery with an input capacity of 300,000 bpd has been planned [77]. The total refining input capacity of the country would more than double, increasing from 63.9 MMbbl/year to 150.5 MMbbl/year [78]. Historically, oil extraction in Ecuador has surpassed demand; around 75% of oil extracted has been exported yearly. However, the projected depletion of domestic endowments, along with the expansion of the refining capacity, may have substantial consequences for Ecuador's trade balance in terms of oil and oil products.

An assessment of the implications of the obtained results was performed using the median of the extraction values for the best-fitted models depicted in Table 9. For this purpose, future oil refining capacity, oil demand, oil products demand, oil exports, oil products imports, and oil products exports were all taken from the work developed by Espinoza et al. [78]. The requirements account for oil used as fuel (own use, electricity generation) and oil feedstock to be processed in refineries. The aim of this differentiation is to determine the physical trade balance of oil demand and supply in Ecuador. As a first approximation, given the low values and opposing sign of refinery gains and conversion losses in the refining process, it is assumed that the volume of oil and oil products is equivalent for the estimation of the physical trade balance of oil.

Two scenarios were considered: Business as Usual (BAU) with current refining capacity and the use of hydropower according to national plans. Energy efficiency policies have not been considered. In this scenario, the combined demand for oil and oil products would increase to 171 MMbbl in 2035 and oil refining capacity would reach 67 MMbbl in the same year. Alternative (ALT) (the “Energy ES” scenario in Ref. [78]) involves the construction of a new refinery, implementing energy efficiency policies based on current national plans, and a substantial use of renewables (mostly hydropower) for electricity generation. In ALT scenario, the combined demand for oil and oil products would reach 111 MMbbl and oil refining capacity would reach 165 MMbbl in 2035. Oil exports were determined as the difference between oil extraction and oil requirements.

As seen in Fig. 6 a), in URR(2P) case, oil extracted might not be able to meet demand in BAU scenario by the year 2024 and would not be enough to satisfy domestic refining capacity by the year 2030. In URR(O) case, in BAU scenario, domestic oil extraction would be surpassed by internal demand in 2028, and it would be able to cover the internal refining capacity in the time frame considered for analysis. Regarding ALT demand scenario, Fig. 6 b) shows that domestic oil extraction would surpass demand in 2027 and 2035, under 2P case and O case, respectively.

Regarding the alternative scenario and 2P case, the new refinery would substantially increase the country's refining capacity. However, oil imports would be necessary from the beginning of operations in 2022. For URR(O) case, oil imports would start in 2024. Given the extraction decrease over the next few decades, the new refinery might be dependent on oil imports for its operation almost from the beginning.

Fig. 6 also shows that Ecuador would go from net oil exporter to net importer, starting in 2024, under 2P Case. In BAU scenario, most of the imports might consist of oil products, given the limited refining infrastructure that would not be able to meet demand. In

ALT scenario, imports would surpass exports in 2027; they would be composed mainly of oil, and the country would be able to export oil products.

Table 10 presents the physical and economic trade balance for oil and oil products based on the median extraction values used for Fig. 6 and oil demand. Exports and imports of oil and oil products (Gasoline, Diesel and LPG, specifically) were considered. For the estimation of future oil product prices, historical, physical and economic trade balance data taken from Ref. [52] and projected oil prices obtained from New Policies Scenario of WEO 2017 [65] were used. A linear regression was performed (see Appendix A) using historical oil prices as an independent variable and historical oil product prices as a dependent variable. Using these regressions, future prices of oil products were obtained based on projected oil prices.

Table 10 and Fig. 7 depict the implications in terms of physical and economic trade balance of the obtained oil extraction projections, faced with 2 plausible demand scenarios for Ecuador in the next few decades. Under URR(2P) case BAU scenario, physical trade balance would be negative by 2024, and the economic trade balance would start to decline in 2020, reaching a deficit of 16.6 billion Dollars by 2035. In the optimistic case (O BAU), the economic trade balance would fall by 50% from 2022 to 2023, become negative in 2025, and reach a deficit of 7.6 billion by 2035. These numbers show that, if current practices in energy supply and demand continue, they would have a profound effect on Ecuadorian economy, which currently counts on oil as a strategic source of income.

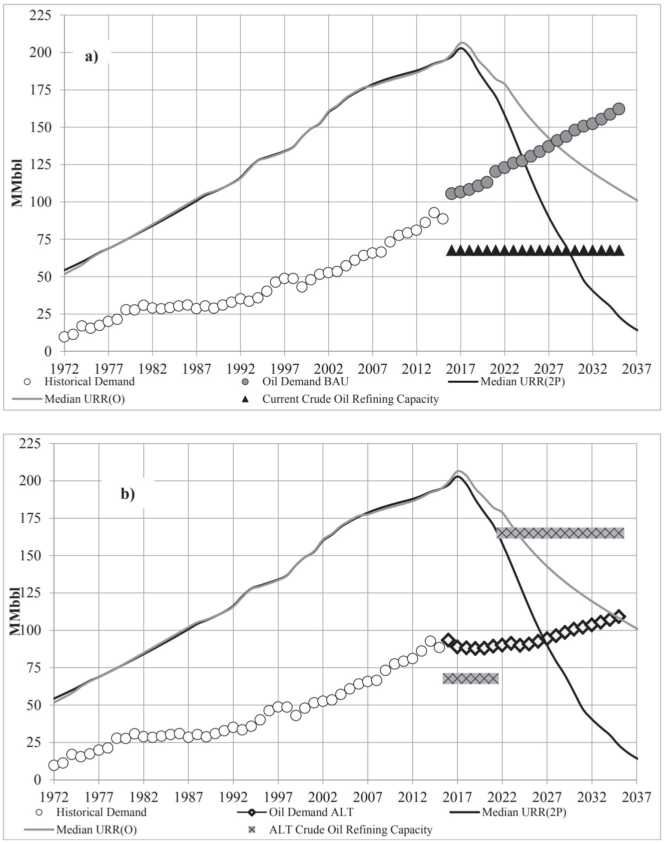

Fig. 6. a): Ecuadorian oil demand, crude oil refining capacity and oil extraction forecast using the medians of the best fitted models for URR(2P) and URR(O). BAU demand, current crude oil refining capacity. b): Ecuadorian oil demand, crude oil refining capacity and oil extraction forecast using the medians of the best fitted models for URR(2P) and URR(O). ALT demand and ALT crude oil refining capacity.

Table 10
Physical and Economic oil trade balance under URR 2P and URR O cases for BAU and Alternative scenarios.

	Physical Trade Balance [MMbbl]				Economic Trade Balance [Million USD 2016]			
Year	2P BAU	O BAU	2P ALT	O ALT	2P BAU	O BAU	2P ALT	O ALT
2016	83.9	87.2	98.0	101.3	1647	1729	2535	2617
2017	80.9	93.3	100.8	113.3	2249	2424	3413	3588
2018	75.7	88.6	98.2	111.0	2255	2567	3659	3971
2019	68.3	77.6	93.9	103.2	1927	2365	3548	3986
2020	59.0	69.0	88.2	98.2	1487	2131	4908	5552
2021	43.4	55.2	78.8	90.6	843	1662	4745	5563
2022	28.4	49.1	66.0	86.7	34	1569	5147	6682
2023	11.5	37.6	51.3	77.4	−1165	898	4213	6276
2024	−4.8	27.9	38.0	70.6	−2421	310	3089	5820
2025	−22.2	17.6	22.9	62.7	−3816	−400	1827	5242
2026	−38.9	7.8	7.7	54.4	−5318	−1217	499	4600
2027	−54.5	−1.7	−6.2	46.6	−6675	−1927	−778	3969
2028	−69.2	−11.2	−18.9	39.2	−8132	−2792	−1993	3348
2029	−81.4	−18.9	−30.4	32.0	−9378	−3497	−3153	2728
2030	−97.1	−28.0	−43.9	25.3	−10,913	−4261	−4545	2107
2031	−111.3	−35.0	−56.7	19.6	−12,458	−4973	−5915	1570
2032	−119.4	−40.9	−64.5	14.0	−13,356	−5447	−6879	1031
2033	−127.9	−47.9	−71.6	8.4	−14,433	−6199	−7755	479
2034	−136.8	−55.0	−79.0	2.8	−15,395	−6860	−8614	−79
2035	−147.3	−62.3	−87.7	−2.7	−16,641	−7663	−9609	−631

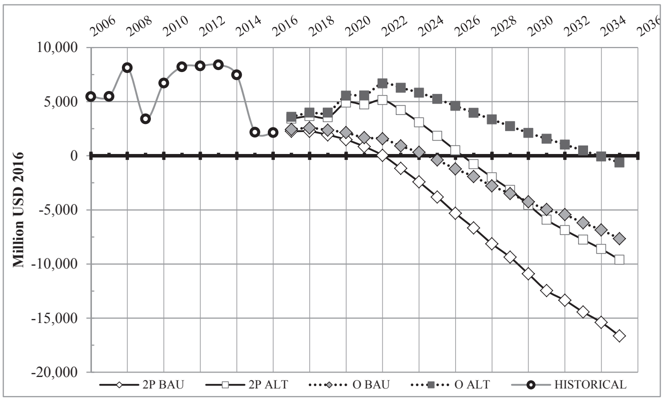

Fig. 7. Economic oil trade balance under URR (2P) and URR(O) cases for BAU and Alternative scenarios.

As mentioned earlier, ALT scenario based on [78] considers energy efficiency strategies such as source and technology substitution, and a substantial introduction of hydropower for electricity generation. Under URR(2P) case, Ecuador might become a net oil importer by 2027. Even if the economic trade balance reaches a deficit of 9.6 billion Dollars by 2035, implementing energy efficiency, introducing renewables in the energy mix, and expanding refining capacity would partially mitigate the impacts. The aim of expanding refining capacity is to reduce imports of gasoline and diesel. Furthermore, costs associated with refinery construction, infrastructure for renewables, and implementation of energy efficiency, have not been considered. The physical trade balance shows that, in ALT scenario, imports would be reduced in 60 MMbbl by 2035 as compared to BAU. Imports in this case would mainly be oil, given that the new refinery outputs would satisfy internal demand for oil products. As expected, URR(O) case presents better results for the period analyzed. The country would become a net importer in 2035, and the deficit in the economic trade balance in the same year would be 0.6 billion Dollars.

Considering the current importance of oil for the Ecuadorian economy, if the country's dependence on this resource persists, the development of an enhanced oil policy is urgent. A solid legal and institutional framework that fosters investment in this area is vital. One of the key points is to modify the contract modality currently used (services) with shared extraction agreements or joint ventures. This has already been addressed by the government and a new bidding round was launched in March 2018 which is expected to attract around 800 million Dollars in foreign investment [79].

Moreover, a thorough analysis ought to be performed to determine whether it is economically viable in the long run to expand the refining capacity. Most of all considering that oil inputs from indigenous extraction would continue to decrease and industrialized economies are putting efforts into making a transition towards renewables and the demand for oil products in the international market might decrease, limiting planned exports. Continuing to depend on oil would imply losing valuable time to prepare a structural transition for the country that might enable it to reduce its reliance on oil as a source of income.

Cases and scenarios analyzed show that Ecuador would be compromised in terms of energy security and in its economy if it continues to depend on oil as its main energy and income source. The most ambitious policies and plans developed so far, considered in ALT scenario in terms of energy efficiency and renewable energy, would only provide short term solutions. Therefore, more aggressive strategies in key sectors are necessary. The main consumer of oil products in Ecuador is the transport sector, which accounts for 46% of the final consumption [52]. This sector is characterized by low efficiency, high levels of pollutants, heavy subsidies, and a small contribution to the economy in terms of the share in GDP [80]. Hence, as oil starts to deplete, a sound strategy seeking to improve efficiency in transport and promote a shift to other fuels (e.g., electricity, sustainable biofuels) and modes (e.g., public transport, non-motorized transport) should be the first concern for decision makers. Furthermore, the Ecuadorian economy relies on oil exports to meet yearly expenditure. As the country already has fiscal deficits, a reduction in income due to oil exports may lead to a strong strain on the Ecuadorian finances, considering that around 23% of total revenues come from oil industry and 48% of total exports were oil over the last ten years. Looking to diversify the productive structure, the external sector and to decrease reliance on oil exports should be a priority, while oil extraction levels in the country and international prices still allow for a soft transition.

5. Conclusions

Future oil extraction projections were performed for Ecuador using Hubbert curves under a national (top-down) and blocks (bottom-up) approach, considering two cases for Ultimate Recoverable Resources (URR) from official data: Proved + Probable Reserves (2P) and Optimistic (O), additionally including possible reserves (3P), contingent resources and prospective (yet-to-find) resources. Given that future extraction may be affected by social and political factors, Hubbert methods allow an estimation to be made of the maximum flow which may be extracted considering geological constraints, given a level of URR. Models that present the best fit to historical extraction in both cases and both approaches considered have Coefficient of variation (Cv) values in the range from 5.0% to 5.7%. The year of maximum extraction lies within the range 2014–2017, except for the National-asymmetric-single-cycle model (2025), and the maximum extraction values are between 196 and 215 MMbbl, a range that includes the historical maximum extraction (203 MMbbl in 2014). Models present steep decline rates; in URR(2P) 50% of maximum extraction would occur from 2024 to 2026 for both approaches. URR(O) case shows different ranges for the years at which 50% maximum extraction would occur, considering the top-down (2037–2040) and bottom-up (2027–2029) approaches. This latter modeling approach, due to its modularity, enables each block to be managed individually, according to future planned requirements. Analysis performed on the blocks showed that having reference points on the falling side of the curve can greatly reduce the error range of the models.

An analysis of the implications that best fitted the models under the URR(2P) case and the Business As Usual (BAU) demand scenario, taken from the bibliography [78], showed that the country could become a net oil importer by 2024 and that the oil trade balance would change from a positive value of 2.2 billion USD in 2016 to a deficit of 16 billion USD in 2035. In the alternative demand scenario (ALT), also taken from Ref. [78], where energy efficiency strategies, expanded refining capacity and use of renewables were considered, based on current national plans, the physical trade balance would be negative in 2027 and the deficit would reach 7.7 billion USD in 2035. In URR(O) case, imports would start in 2027 and 2035, and the trade balance deficit would reach 9.6 and 0.6 billion USD in 2035 for BAU and ALT scenarios, respectively.

If Ecuador's dependence on oil as a source of energy and income continues, the country's energy security and economic stability will be compromised in both the short and long term. Although initiatives regarding energy efficiency and the penetration of renewables have been planned, they would not be enough in the long run. It is then a priority to consider more ambitious plans focused on sectors with high consumption levels and low contribution to the economy. A more aggressive penetration of renewables is also critical for a fossil fuel phase-out. Furthermore, diversifying the Ecuadorian productive structure should be a priority for decision makers, given that it is the only way to reduce the strategic role of oil in the country's economy. Further work should also be focused on studying alternatives that can reduce Ecuador's dependence on oil for economic and energy purposes.

Main limitations found in the work are related to the variability of the curves, neglecting the influence of technological and political factors in future forecasts and in URR variations, as well as the difficulty to foresee future extraction cycles that, as seen in the past, do not depend solely on geological factors. Future research could explore how models not based on bell-shaped curves compare with the results in this study. See for example the work carried out by Mohr describing the extraction of mineral and oil resources as a compounded set of exponential growth, plateau and exponential decrease. Also, to study the outcomes of this study in greater depth, it would be worth including how commodity price variations affect extraction results, using econometric forecasting linked to geological-based models, such as the ones tested in this work.

Appendix A

To determine the average price of Ecuadorian Crude Oil and imported oil products, information from the National Energy Balance was retrieved [52]. As a first approximation, a linear relationship between crude oil prices and the respective oil products was assumed. Crude oil imports and oil products in physical and monetary units in Tables A1 and A.2, respectively, were used to calculate the average price for gasoline, diesel and LPG.

Table A.1
Oil trade Balance for Ecuador (MMbbl)

Year	Crude Oil Exports MMbbls	Oil products imports MMbbl		
		Gasoline	Diesel	LPG
2012	124	14	17	9
2013	134	16	21	10
2014	149	20	25	11
2015	146	19.5	23.7	10.8
2016	139	16	18.1	9.9

The Crude Oil Price obtained from the New Policies Scenario of the WEO 2017 [65] was plotted as an independent variable versus Gasoline, Diesel and LPG prices, respectively. A linear regression was performed, obtaining equations with a correlation coefficient higher than 0.9, as seen in the results depicted in Figures A.1, A.2, and A.3.

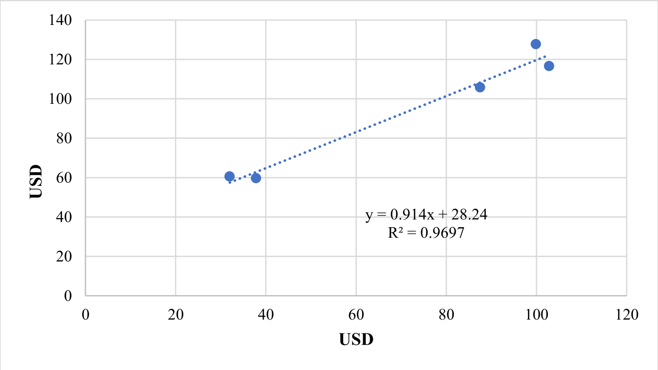

Fig. A.1. Linear regression Crude oil price vs Gasoline Price.

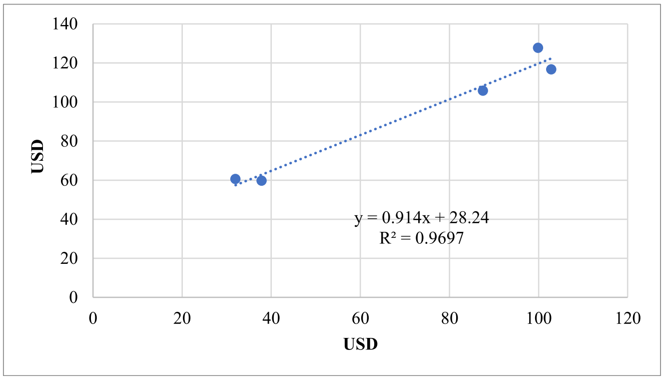

Fig. A.2. Linear regression Crude oil price vs Diesel Price. 2

Table A.2
Oil trade Balance for Ecuador (MMUSD)

Year	Crude Oil Exports MUΣ	Oil products imports MMUSD		
		Gasoline	Diesel	LPG
2012	12,711	1663	1974	771
2013	13,412	2048	2318	644
2014	13,016	2108	2746	658
2015	5539	1161	1791	397
2016	4441	970	1018	314

Table A.3
Estimated Crude Oil and Oil product prices (USDBbl)

Year	Crude Oil Price UΣ/Bbl	Oil product price USD/Bbl		
		Gasoline	Diesel	LPG
2012	102.8	116.6	116.0	85.5
2013	99.9	127.7	111.2	67.3
2014	87.5	105.8	110.0	61.3
2015	37.8	59.6	75.6	36.7
2016	32.0	60.6	56.4	31.7

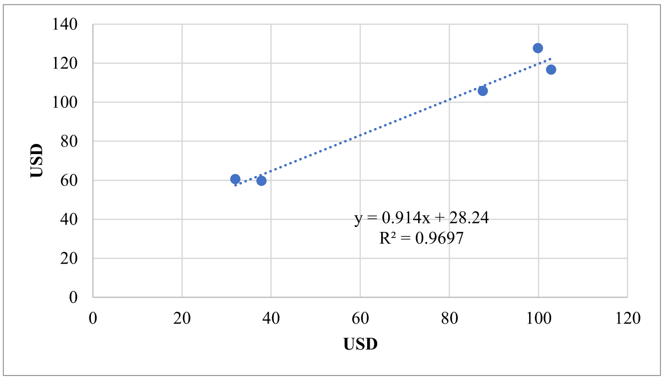

Fig. A.3. Linear regression Crude oil price vs LPG Price. 3

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2019.06.061.

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