Oil-to-Chemicals: Technological Approaches and
Advanced Process Configurations

Updated Multi-Client Study Proposal

September 2017
Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations

I. INTRODUCTION

This TCGR multi-client study was launched in August 2017 and is slated for completion in November 2017. The study’s scope, and specific contents (as depicted in the ToC on page 8 of the proposal, available via download here), reflect the inputs from a group of “charter” subscribers who have indicated their priorities for coverage, areas to be expanded/deepened and focal points for emphasis in opportunity identification. These are leading industrial integrated refiners and petrochemical producers and users.

There is a need for an objective assessment and detailed technological analysis of the activities directed towards oil-to-chemicals pursuits. It is clear that among the leading positions/approaches developed to date, notably by ExxonMobil and Saudi Aramco, the full breadth of the potential need may not be addressed because each user will require a unique solution. Therefore it would be useful to evaluate the olefins and/or aromatic needs of chemical plants in reverse order, back towards the intake of crude oil using different existing and new technologies that may prove more economical at smaller scale than the massive CAPEX schemes currently being proposed by licensors, as solutions. Beyond these leading activities, numerous independent technology developers like UOP/Honeywell, Axens, CB&I and other majors like SABIC are working towards combinations of technologies which can achieve a similar objective.

TCGR’s proposed assessment, entitled “Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,” will take an end-market based approach, using numerous subscriber-defined case studies, with the objective of documenting the available technologies, plus those in development (including the needed combinations) to maximize the return on conversion based on product slate (chemicals/petrochemicals and specialty/intermediates). Such optimization will be required if such practices are expected to be competitive with low-cost thermal cracker routes as well as increasingly large aromatics complexes based on scale.

The results will provide practitioners, developers and prospective partners/evaluators, especially the major global chemical (olefins, aromatics) producers, with the tools needed to evaluate technology options in specific case study applications, via mixing and matching unique solutions, in order to determine viability in practice or worthiness of further investment.

II. BACKGROUND

The movement towards the production of chemicals and petrochemicals such as olefins and aromatics directly from crude oil, as opposed to via thermal cracking of naphtha/ethane (for olefins) and via traditional refining reforming (for aromatics), is being driven by numerous
factors, the most important of which is the imbalance between demand for oil-derived liquid fuels (diesel, gasoline) and the more rapid growth in markets for petrochemicals like olefins (ethylene, propylene), aromatics (BTX) and specialty intermediate streams like C\textsubscript{4}s and higher olefins. The imbalance has made the idea of using crude as a direct feedstock more appealing for integrated producers of fuels and chemicals as well as direct chemical companies.

![Figure 1. The Imbalance between Growth for Oil-derived Fuels (Diesel, Gasoline) vs. Petrochemicals/Chemicals (Olefins, BTX, etc.) is Driving Crude-to-Chemicals Considerations](image)


The technologies for these novel, and important, chemical/petrochemical production processes are being pursued by industry leaders like ExxonMobil and Saudi Aramco/SABIC, but will also affect the competitiveness of peer participants, i.e. all chemical producers, as well as EPCs, process licensors and technology developers like CB&I, Axens, UOP/Honeywell. Added to this are traditional routes being potentially made uncompetitive, such as naphtha cracking, and there is strong, widespread and urgent interest in approaches to, and justification for, these opportunities/threats.

Depending on the crude oil feedstock, the avoidance of refinery fuels production and using specialty hydrocracking (HC) processes to naphtha or via fluid catalytic cracking (FCC) to olefins or BTX could provide lower costs than participating in the current/historical refinery value chain. As an example, CP Chem’s Aromax™ can provide BTX from olefins and the resid FCC unit could be more inexpensively tailored towards C\textsubscript{2}− and C\textsubscript{3}− olefins production, rather than the more costly and less selective steam cracking of naphtha.
In its proposed multi-client study entitled “Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,” TCGR will take a market-driven approach towards technology development, availability and implementation, to capture viable routes (including technology combinations) to allow the oil-to-chemicals practitioner to practice and profit from various feedstock conversion routes. The study’s breadth will include a range of crude oils (heavy to light) plus bio-crudes, as well as a range of product slates from propylene-focused to a mix of chemicals, including specialty/C₄s. Included are three major market segments for chemicals/petrochemicals from the processes: (1) olefins; (2) aromatics; and (3) specialty/intermediates (e.g., C₄ and higher olefins). The emphasis will be on economically viable or developing technological solutions for cost-effective chemical/petrochemical supply via direct oil-to-chemicals routes.

Of particular interest to chemical producers is how from the end-product (e.g., BTX) can you back integrate into the best configuration for costs based on the crude oil type and are there attractive margins to consider these new configurations/combines?

III. THE NEED FOR THE STUDY

The documentation to date has been centered on ExxonMobil and Saudi Aramco/SABIC comparisons, each of which has its own internally-derived rationale for pursuing oil-to-chemicals, whether it is taking advantage of the imbalance in growth rates between chemicals/petrochemicals and fuels or the need to further add value to crude oil resources providing higher rates of returns on investments. In many cases, others in the chemicals/petrochemicals industries may have different needs for the output or preferred routes/relationships with technology licensors or developers to get there. In TCGR’s independent, detailed technological assessment, analytical and critical perspectives will be taken, across alternative approaches, to ensure that both the benefits and costs are considered. It will also highlight the state of availability/development of the technologies, alone or in combination, so that a mix and match approach can be assessed.

Today, most have only seen the reports from various sources, including IHS Chemicals’ Process Economics Program (PEP) which explains and benchmarks ExxonMobil’s Singapore plant compared against Saudi Aramco’s patents. Others may be familiar with recent references such as SABIC’s presentation at the ME-TECH (Feb. 2017; Dubai) and/or CB&I’s presentation from the MERTC conference (Jan. 2017; Bahrain). Notably, there is the Corma paper “Crude to Chemicals: Light Olefins from Crude Oil” (Catal. Sci. Technol., 2017, 7, 12-46) which provides a review of resid FCC upgrading but does not adequately appreciate resid hydrocracking (HC) or catalytic steam cracker (CSR) advances, although there is a brief review of Sinopec’s catalytic pyrolysis process (CPP).
Figure 2. Refining Strategies to Maximize Light Olefins from Crude Oil

Source: Corma, 2017

Table 1
Main Processes Dedicated to Crude Oil Cracking with Circulating Solids, Operating Conditions, and Ethylene Yields (adapted from Matsunami et al., Hydrocarbon Process., 1970, 49(11), 121-26)

<table>
<thead>
<tr>
<th>Licensor</th>
<th>BASF</th>
<th>BASF</th>
<th>Chiyoda chemical</th>
<th>UBE</th>
<th>Lurgi</th>
<th>Gulf/S&amp;W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process/bed</td>
<td>Fluid bed</td>
<td>Jet flow</td>
<td>Fluid bed</td>
<td>Fluid bed</td>
<td>Fluid bed</td>
<td>Fluid bed</td>
</tr>
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<td>type</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Crude oil</td>
<td>Minas</td>
<td>Minas</td>
<td>Khafji</td>
<td>Minas</td>
<td>Irak</td>
<td>n/a</td>
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<tr>
<td>Heat supply</td>
<td>Coke burning</td>
<td>Coke</td>
<td>Coke partial</td>
<td>Coke burning</td>
<td>Coke</td>
<td>Coke burning</td>
</tr>
<tr>
<td>Particles in bed</td>
<td>Coke</td>
<td>Coke burning</td>
<td>Coke partial</td>
<td>Coke burning</td>
<td>Coke</td>
<td>Coke burning</td>
</tr>
<tr>
<td>Temperature/°C</td>
<td>725</td>
<td>760</td>
<td>850</td>
<td>840</td>
<td>760</td>
<td>750</td>
</tr>
<tr>
<td>Yields (wt%)</td>
<td>41.5</td>
<td>41.5</td>
<td>37.6</td>
<td>47.8</td>
<td>41.6</td>
<td>n/a</td>
</tr>
<tr>
<td>C2–C4 olefins</td>
<td>23</td>
<td>23</td>
<td>26.8</td>
<td>28.1</td>
<td>23.1</td>
<td>22.5</td>
</tr>
<tr>
<td>Ethylene</td>
<td>12.5</td>
<td>11.2</td>
<td>5.8</td>
<td>11.3</td>
<td>12.8</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Source: Corma, 2017
Key questions to be addressed in the study include how chemical companies can target this technology opportunity - from an olefins and aromatics/BTX chemical plant feedstock point of view - but enhance the olefins and/or BTX yields even higher through retrofit catalysts and known process technology incremental revamps?

What is needed is to document recent catalyst and process advances relevant to olefins and BTX chemical products that avoid the upfront investment in catalytic distillation units (CDUs) and vacuum distillation units (VDUs) and other parts of the refinery while maximizing BTX and olefin yields (primarily C₃+, and C₄+) beyond typical refinery economics and normal/known process configurations that have historically been optimized for fuels production.

**Table 2**

**Analysis of Crude to Chemicals Complexes: Case Studies**

<table>
<thead>
<tr>
<th></th>
<th>Minimum Investment; No Resid Upgrader; No Fuels; Sell HSFO</th>
<th>LC-FINING; No Fuels; Sell LSFO</th>
<th>LC-FINING With Fuels; Sell LSFO</th>
<th>LC-FINING With Delayed Coking; No Fuels; Two Train Cracker</th>
<th>LC-FINING + Slurry With Fuels; Produce Anode Coke</th>
<th>LC-FINING + Slurry With Fuels; Produce ULSFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude (Arab Light), BPD</td>
<td>195,000</td>
<td>162,000</td>
<td>227,000</td>
<td>400,000</td>
<td>137,689</td>
<td>246,515</td>
</tr>
<tr>
<td>Ethylene, KTA</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>4,000</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Propylene, KTA</td>
<td>1,480</td>
<td>1,493</td>
<td>1,469</td>
<td>2,805</td>
<td>1,481</td>
<td>1,489</td>
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<tr>
<td>Butadiene, KTA</td>
<td>357</td>
<td>358</td>
<td>347</td>
<td>774</td>
<td>373</td>
<td>326</td>
</tr>
<tr>
<td>Euro VI Diesel, BPD</td>
<td>0</td>
<td>0</td>
<td>74,500</td>
<td>94,265</td>
<td>0</td>
<td>106,000</td>
</tr>
<tr>
<td>Fuel Oil, BPD</td>
<td>54,000</td>
<td>25,000</td>
<td>20,000</td>
<td>36,935</td>
<td>0</td>
<td>8,500</td>
</tr>
<tr>
<td>Anode Coke, KTA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>194</td>
<td>0</td>
</tr>
<tr>
<td>H₂ Required, MMSCFD</td>
<td>167</td>
<td>251</td>
<td>379</td>
<td>665</td>
<td>282</td>
<td>417</td>
</tr>
<tr>
<td>% Required H₂ from Cracker</td>
<td>39</td>
<td>26</td>
<td>18</td>
<td>22</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Natural Gas Required, KTA</td>
<td>596</td>
<td>777</td>
<td>1,011</td>
<td>1,872</td>
<td>794</td>
<td>992</td>
</tr>
<tr>
<td>Chemical Yield on Crude, %</td>
<td>58</td>
<td>70</td>
<td>49</td>
<td>57</td>
<td>83</td>
<td>45</td>
</tr>
<tr>
<td>Total Project Cost, MM$</td>
<td>6,954</td>
<td>7,995</td>
<td>8,910</td>
<td>14,173</td>
<td>8,492</td>
<td>9,285</td>
</tr>
<tr>
<td>%IRR</td>
<td>14.6</td>
<td>22.4</td>
<td>24.4</td>
<td>33.0</td>
<td>21.4</td>
<td>25.0</td>
</tr>
</tbody>
</table>

**Notes**

1. 3% HSFO 1% LSFO 1% LSFO 1% LSFO Anode Coke 0.1% ULSFO
2. All cases includes Hydrocracker + Olefins Conversion Technology
3. All cases produces MTBE, Butene-1, Benzene, Xylenes
4. 3% HSFO priced at $21/Bbl less than crude
5. %IRR based on 70 / 30 debt / equity ratio

Source: CB&I, 2017

**IV. SCOPE AND METHODOLOGY**

Oil-to-chemicals routes for three (3) product groups, via numerous case study approaches, will be addressed as follows: 1) olefins; 2) aromatics; and 3) specialty/intermediates (e.g., C₄s and higher olefins)

The study will include coverage addressing:
Upstream to the feedstock/oil source, in order to differentiate between pre-treatment steps (if required)
  - Heavy/sour crudes: S. America, Russia/Urals; Canadian tar sands; opportunity crudes

Product slate via technology approach, i.e., %olefin by carbon (C₂, C₃, C₄, etc.).
  - Ethylene, propylene, C₄ and higher olefins

Implications on technology implementers, to assess economic/financial metrics (CAPEX, product costs, ROI, etc.)
  - Steam cracker modifications, combinations/integrations, etc.

Advancements in technology (catalysts, processes, combinations) yielding novel options for consideration/evaluation in retrofit

Impacts on technology developers and users, to gauge readiness levels and timing of commercial impacts
  - Practitioners, licensors, developers, etc.

Potential end-market and competitor-supplier implications, indicating likely winners and losers
  - Optimal crude/product combinations, integrated vs. independent suppliers, etc.

The scope will include numerous case studies, determined by the study’s “charter” subscribers (i.e., those who committed to supporting it prior to formal launch) with consideration of the following:

- Modified steam crackers; catalytic steam cracking
- Gasoil/steam cracking, gasoil/HSFCC
- Resid FCC: Multiple riser systems, R2R, Milos (Shell), HSFCC (Axens)
- Hydrocracker/FCC; Flexicoking/FCC; FCC/Reforming
- H-Oil and slurry HC (IFP); LC Fining (Lummus/CB&I)
- Hydroconversion upgrader (GHU, Genoil)
- Ebullated bed – EST (Eni)
- Pyrolysis catalytic cracking (PCC)
- Deep catalytic cracking (DCC)
- Aromax (CP Chem), Cyclar (UOP/Honeywell), etc.
- Others (to be determined via “charter” subscriber input)
Table 3
Representative Advances in Oil-to-Chemicals Technologies: Upping Olefins and BTXs

<table>
<thead>
<tr>
<th>Conventional Process Type</th>
<th>Upping Olefins C₂⁺, C₃⁺, C₄⁺ Highs</th>
<th>Upping BTX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resid FCC R2R, Milos</td>
<td>C₃⁺, C₄⁺’s ZSM5 additives and HSFCC, Milos and double gen.</td>
<td>BTX additives</td>
</tr>
<tr>
<td>Downer Reactor</td>
<td></td>
<td>Ga H-ZSM 5 (UOP Cyclar)</td>
</tr>
<tr>
<td>DCC (Sinopec)</td>
<td>C₄⁺’s Zeolite Beta</td>
<td>P&amp;L zeolite (Aromax)</td>
</tr>
<tr>
<td>Resid FCC-Least CAPEX</td>
<td>C₅⁺’s Ferrierite (Petrobras)</td>
<td></td>
</tr>
<tr>
<td>With C₂⁺ from ethane cracking C₂⁺ selectivity may not be so desirable</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HC ex CB&amp;I/other</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HOPS (CB&amp;I) Removes Heavy Residue thermal cracking cracks &lt; 550˚C and below eliminates CDU + VDU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isocracking (Chevron) still VDU +CDU. Resid HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LC Slurry Options (best IRR) EST H-Oil+Slurry LC Fining (CAPEX 8BIL IRR 22.4%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Catalytic Steam Cracking | | |
|--------------------------| | |
| Thermal Cracking (Corma, 2017) | | |
| CCP (Sinopec) RIPP Dow Process | | |

Source: TCGR, 2017

Via a market-driven approach documenting detailed technological assessments (including combinations) as determined by the industry’s leading participants as “charter” subscribers, TCGR’s study will present a state-of-the-art assessment in oil-to-chemicals approaches to addressing the imbalance between olefin supply/demand in this uncertain but opportunistic period.

TCGR will use in-house and external resources, as well as expertise from within industry as well as our highly-regarded DIALOG GROUP ® in order to complete:
- Technology evaluations
- Patent reviews and analyses
- Representative economics
- Market needs/drivers
- Competitive implications (developers vs. users)

A refined/expanded Table of Contents is provided on the following page in order to depict the breadth and depth of the study as envisioned.

References
CB&I, 2017; Crude to Chemicals: Opportunities and Challenges of an Industry Game-Changer; MERTC, Bahrain
IEA, 2016
IHS, 2016
OPEC, 2016
Platts, 2016
Final Table of Contents*
OIL-TO-CHEMICALS: TECHNOLOGICAL APPROACHES AND ADVANCED PROCESS CONFIGURATIONS

I. BACKGROUND/INTRODUCTION

II. EXECUTIVE SUMMARY

III. THE NEED FOR OIL-TO-CHEMICALS: MARKET SIZE/GROWTH: OLEFINS, AROMATICS AND INTERMEDIATES/SPECIALTIES
   A. Olefins
   B. Aromatics
   C. Intermediates/Specialty (e.g., C4 and higher olefins, etc.)
   D. The Imbalance between Oil for Fuels vs. Oil for Chemicals
   E. Opportunity Light Crudes
   F. Opportunity Assessment, Whole Crude Cracking

IV. OIL-TO-CHEMICALS: OLEFINS
   A. Current Approaches
      1. Steam Crackers – ExxonMobil vs. Saudi Aramco approaches (the benchmarks)
      2. FCC
      3. PDH
      4. Others (via “charter” subscriber inputs)
   B. Advancements and Enabling Technologies (oil-derived olefins)
      1. Cracker modifications
      2. HC
      3. DCC
      4. CPP (Sinopec)
      5. Others (via “charter” subscriber inputs)
   C. Remaining Hurdles (technical, economic) and heavies upgrading (recycle)
   D. Assessment

V. OIL-TO-CHEMICALS: AROMATICS
   A. Current Approaches and Advancements/Enabling Technologies (oil-derived aromatics)
      1. Resid FCC --> olefins -> aromatics
      2. Aromax, Cyclar, etc.
      3. Others (via “charter” subscriber inputs), e.g. extraction (benzene and other)
   B. Remaining Hurdles (technical, economic)
   C. Assessment

VI. OIL-TO-SPECIALTY/INTERMEDIATE STREAMS (C4, C5 AND HIGHER OLEFINS, ETC.)
   A. Current Approaches and Advancements/Enabling Technologies (oil-derived higher olefins)
      1. Traditional refining/cracking
      2. Direct C1 conversion
      3. Resid FCC --> lower olefins -> higher olefins
      4. Others (via “charter” subscriber inputs)
   B. Remaining Hurdles (technical, economic)
   C. Assessment

VII. COMPETITIVE/STRATEGIC IMPLICATIONS
   A. Prospects for Economically Viable Routes
   B. Technical/Market Participants Affected
   C. Competitive/Market Reactions to Changes
   D. Strategic Implications, why crude-to-chemicals makes sense.

VIII. CONCLUSIONS AND RECOMMENDATIONS

*TofC reflects “charter” inputs (those who subscribed prior to launch)
V. QUALIFICATIONS

The Catalyst Group Resources, a member of The Catalyst Group, works with clients to develop sustainable competitive advantage in technology-driven industries such as chemicals, refining, petrochemicals, polymers, specialty/fine chemicals, biotechnology, pharmaceuticals, and environmental protection. We provide concrete proven solutions based on our understanding of how technology impacts business.

Using our in-depth knowledge of molecular structures, process systems, and commercial applications, we offer a unique combination of business solutions and technology skills through a range of client-focused services. Often working as a member of our clients' planning teams, we combine our knowledge of cutting-edge technology with commercial expertise to:

- Define the business and commercial impacts of leading-edge technologies
- Develop technology strategies that support business objectives.
- Assess technology options through strategy development, including:
  - Independent appraisals and valuations of technology/potential
  - Acquisition consulting, planning and due diligence
- Provide leading-edge financial methodology for shareholder value creation
- Lead and/or manage client-sponsored R&D programs targeted through our opportunity identification process.
- Provide leading information and knowledge through:
  - World-class seminars, conferences and courses
  - Timely technical publications

The client-confidential assignments conducted by The Catalyst Group include projects in:
- Reinventing R&D pipelines
- Technology alliances
- Technology acquisition
- Market strategy

We have built our consulting practice on long-term client relationships, dedication, and integrity. Our philosophy is clear and focused:

We Provide the "Catalysts" for Business Growth by Linking Technology and Leading-Edge Business Practices to Market Opportunities
VI. DELIVERABLES AND PRICING

This report is timely and strategically important to those industry participants and observers both monitoring and investing in the development and implementation of technologies for the conversion of oil-to-chemicals. TCGR’s report, based on technology evaluations, commercial/market assessments and interviews with key players will go beyond public domain information. As a result, subscribers are requested to complete and sign the “Order Form and Secrecy Agreement” on the following page.

The study, “Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations” is expected to be available in November, 2017.

<table>
<thead>
<tr>
<th>Participation</th>
<th>Deadline</th>
<th>Price</th>
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<tr>
<td>Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations</td>
<td>after June 23, 2017</td>
<td>$23,500</td>
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<td>Post-launch subscribers</td>
<td></td>
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<tr>
<td>Oil–to–Chemicals: Technological Approaches and Advanced Process Configurations</td>
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<td>$1,000</td>
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<tr>
<td>Report in PDF format, in addition to subscription price</td>
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</table>

* Charter subscribers (those who signed up for the study before June 23rd, 2017) had the opportunity to work with TCGR to further refine the scope of the report by nominating specific case study content as well as delineating areas of particular interest for inclusion in the assessment.
ORDER FORM AND SECRECY AGREEMENT
The Catalyst Group Resources, Inc. Tel: +1.215.628.4447
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P.O. Box 680 e-mail: tcgr@catalystgrp.com
Spring House, PA 19477 - USA - website: www.catalystgrp.com

Please enter our order for “Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,” to be completed in November, 2017, as follows:

____ “Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,” for $23,500 (after study launch)

____ Please enter our order for the study to be delivered in PDF (Adobe Acrobat) format for use across our sites/locations (i.e., site license) for an additional $1,000.

____ Please send us ______ additional printed copies @ $250 each.

In signing this order form, our company agrees to hold this report confidential and not make it available to subsidiaries unless a controlling interest (>50%) exists.

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