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Tesi di Laurea Magistrale

Floating Liquefied Natural Gas (FLNG) *vs* conventional Natural Gas (NG) supply chains: energy and environmental sustainability perspectives

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Nonostante il gas naturale (NG) sia notoriamente raggruppato insieme con gli altri combustibili fossili, possiede delle caratteristiche che gli conferiscono unicità in grado di rispondere alle necessità dell'attuale scenario energetico globale. Come noto, infatti, i combustibili fossili che oggi sorreggono principalmente il sistema socio-economico e la crescita mondiale [1] sono caratterizzati da due fondamentali problematiche: sono risorse destinate ad esaurirsi nei prossimi c. 100 anni [2] (trattandosi di risorse non rinnovabili, il cui sfruttamento supera di gran lunga il loro tempo di rinnovo), e il loro utilizzo comporta impatti ambientali sostanziali. In particolare, il loro sfruttamento è stato collegato ai fenomeni osservabili legati al cambiamento climatico, primo tra tutti l'incremento di temperature. Tuttavia, come anticipato, il NG si differenzia rispetto agli altri fossili. Questo infatti, nonostante sia comunque una fonte in esaurimento, ha il vantaggio di essere nettamente più pulito. Il suo utilizzo è infatti associato a c. il 29-44% in meno di emissioni di CO_2 per un'unità di energia liberata. Inoltre rispetto al petrolio e al carbone sono emesse minor quantità di inquinanti: c. 80% di NO_x in meno, c. 99,99% di SO_2 in meno, e c. 95% di particolato in meno. Inoltre, il NG si differenzia soprattutto per la sua adattabilità: la sua catena di approvvigionamento può potenzialmente essere sfruttata dai combustibili rinnovabili, quali syngas, biogas e bio-metano. In particolare, questi ultimi, si prevede che occuperanno, anno dopo anno, una fetta sempre maggiore del mix energetico mondiale. È dunque per le ragioni esposte, che al NG è stato attribuito il ruolo di *combustibile di transizione* verso un'economia caratterizzata da basse emissioni di gas ad effetto serra (GHG), improntata ad accogliere gli obiettivi mondiali volti alla mitigazione di questi.
A dimostrazione di quanto esposto, e in accordo con i recenti report della British Petroleum (BP) [4], l'incremento del consumo energetico dell'1,3% registrato dal 2019 al 2021, è stato guidato dall'aumento dell'utilizzo di combustibili rinnovabili. I combustibili fossili, al contrario, nonostante siano rimasti invariati come percentuale nel loro complesso, hanno registrato una diminuzione della domanda di petrolio (-8 EJ), a fronte di un aumento di quella di NG (+5 EJ) e carbone (+ 3EJ). Inoltre, secondo i dati raccolti dalla BP, il NG soddisferà c. un quarto della domanda energetica globale entro il 2030. La Fig. 1.3 mostra le future proiezioni della domanda di NG. È interessante notare, a valle di un'attuale richiesta crescente, che è previsto il raggiungimento di un plateau intorno al 2050.
Considerando dunque l'importanza crescente attribuita a questo combustibile, nonché il ruolo che è destinato a ricoprire verso la transizione energetica, il lavoro di tesi presentato mira ad analizzare, da un punto di vista di impatti ambientali e sostenibilità energetica, le diverse catene di approvvigionamento ad esso correlate.
Ad oggi, il NG è trasportato principalmente attraverso due metodologie. La prima, quella maggiormente adoperata (c. il 70% del NG segue questa catena), prevede lo sfruttamento dei gasdotti. Nella seconda opzione invece, il NG viene liquefatto e trasportato attraverso apposite metaniere (LNG carrier). Tuttavia, vista l'ingente crescita della domanda, negli ultimi anni è stata posta attenzione anche sugli abbondanti ma piccoli giacimenti che si trovano in mare aperto. Il loro sfruttamento induce alla revisione degli impianti convenzionalmente impiegati a questo scopo, in quanto, la loro costruzione, potrebbe non essere fattibile sia da un punto di vista tecnico che economico. È proprio in questo contesto che negli ultimi anni sono emerse le cosiddette piattaforme *Floating Liquefied Natural Gas* (FLNG). Si tratta di imbarcazioni dalle ingenti dimensioni (la loro lunghezza può raggiungere quasi i 500 metri) in grado di estrarre, trattare e liquefare il NG. Questo sistema permette inoltre di adattare flessibilmente domanda e consumo e, soprattutto, di diminuire le attuali costrizioni geopolitiche dovute alla dipendenza di alcuni paesi rispetto ad altri, per la fornitura del combustibile. Lo sviluppo del concetto dell'FLNG, nasce intorno al 1950. Ad oggi, i principali progetti in funzione includono: Shell Prelude, Petronas I e II, e Coral Sul. In particolare, in questa tesi, il progetto Coral Sul, è stato

valutato in dettaglio come caso di studio. Tra tutte, questa imbarcazione, risulta essere la più giovane: il primo carico prodotto è stato spedito il 13 novembre del 2022. Questa, inoltre, è stata progettata per sostenere un carico produttivo di 3,4 milioni di tonnellate all'anno (mtpa) di LNG, che sono l'equivalente di 5 miliardi di metri cubi (bcm) di NG. Per avere un'idea più chiara rispetto questa quantità, si consideri che nel 2021 il consumo di NG in Italia e in Svizzera ha raggiunto rispettivamente i 76,1 bcm e i 3,6 bcm. Di conseguenza Coral, sarebbe potenzialmente in grado di soddisfare c. il 6,57% e il 139% della domanda di combustibile in questi Paesi.
Da un punto di vista ingegneristico, considerare la filiera dell'FLNG/LNG o dell'NG presenta delle differenze. In generale questa è costituita da tre fasi principali:

- *Upstream*: produzione (o estrazione) e trattamento del NG grezzo.
- *Midstream*: trasporto.
- *Downstream*: stoccaggio e distribuzione all'utilizzatore finale.

Questi tre step, sono raffigurati schematicamente in Fig. 1.4, dove vengono inoltre evidenziate le principali differenze tra le due opzioni. Si ricordi, che l'unica differenza che intercorre tra LNG e FLNG, è che tutte le fasi, dall'estrazione alla liquefazione, avvengono interamente sull'imbarcazione. Nel caso dell'LNG invece, il trattamento e la produzione possono avvenire, a seguito di un appropriato sistema di trasporto, in due impianti geograficamente distanti.

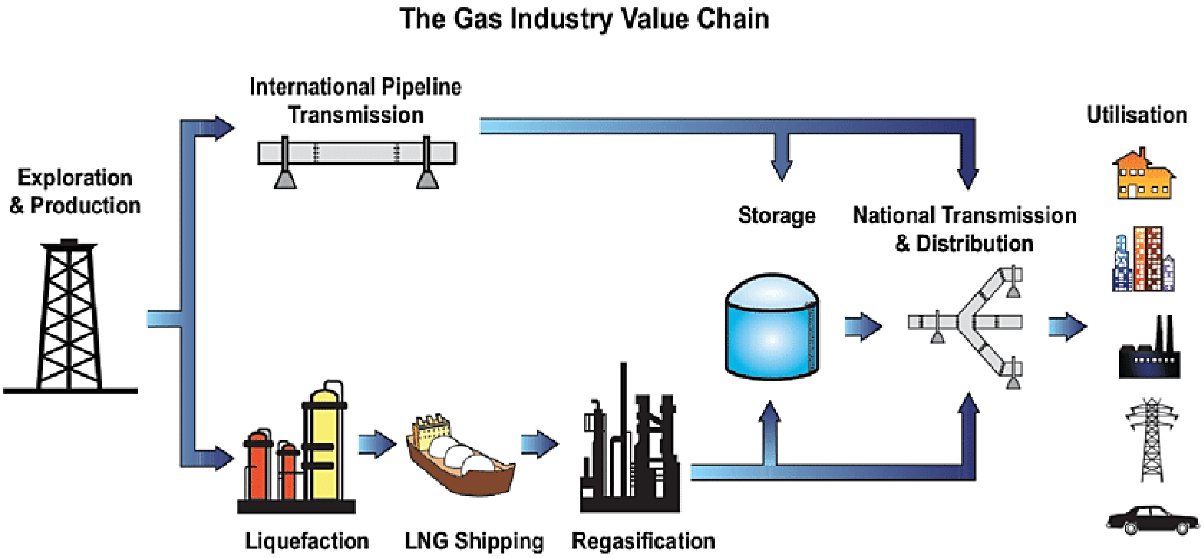

Figura 1.4: Le due principali catene di approvvigionamento del NG. Figura presa da [9] con modifiche.

Le prime differenze tra NG e LNG si possono riscontrare nella fase di trattamento, che convenzionalmente include le unità di: addolcimento, disidratazione, e recupero e frazionamento di NGL (idrocarburi appartenenti al range C_2-C_5). Nel caso dell'LNG (o FLNG), sono previste unità aggiuntive, quali quella di rimozione del mercurio e quella volta liquefazione. In questo caso infatti, il gas greggio deve essere sottoposto a trattamenti di pulizia più intensivi, volti alla rimozione di inquinati (tra cui il mercurio) che causerebbero problemi nel successivo processo di liquefazione. Quest'ultimo in particolare, prevede di raffreddare il gas a temperature criogeniche, che raggiungono i -162°C. La ragione per cui il gas viene portato nella sua forma liquida, è la conseguente facilità e ottimizzazione nel trasporto. A seguito del trattamento criogenico, infatti, il suo volume viene ridotto fino a 600 volte, consentendo così il suo trasferimento attraverso le metaniere. Quest'ultime consegneranno il combustibile in terminal prestabiliti, dove il NG verrà nuovamente convertito nella sua forma gassosa, grazie

ad opportuni impianti di rigassificazione. Da qui, le due catene (NG e LNG) seguiranno un percorso comune, che include l'eventuale stoccaggio, e la distribuzione attraverso lo specifico sistema di gasdotti nazionale, con il quale verrà raggiunto l'utilizzatore finale.
Gli impatti ambientali di tutte le filiere sono di grande importanza per gli attuali obiettivi di mitigazione dei cambiamenti climatici. Dunque, come anticipato, lo scopo di questa tesi è quello di valutare le opzioni disponibili per la fornitura di NG, analizzandone le diverse catene da un punto di vista di impatti ambientali e sostenibilità energetica, puntando tuttavia la lente di ingrandimento sull'emergente FLNG.
Per introdurre il concetto di "sostenibilità energetica" e "impatto ambientale", è utile considerare la realtà fisica come descritta dall'interconnessione di tre sfere: biofisica, antropologica, e tecnologica. In questa prospettiva, un'attività antropologica si traduce in flussi di materia e di energia che si muovono dalla sfera biofisica (l'ambiente naturale) a quella antropologica, al fine di sostenere i diversi bisogni dell'uomo. Tuttavia, questi flussi sono destinati a ritornare nella biosfera, sotto forma di rifiuti. In particolare, al fine di muoversi verso un sistema socio-economico sostenibile, è necessario investigare e migliorare la tecnosfera.
Brevemente, la traiettoria di un flusso energetico può essere descritta come un'*energia primaria* (risorsa estratta direttamente dalla biosfera) che, dopo una prima trasformazione, è convertita in un vettore energetico (*energy carrier*) al fine di essere trasportata o stoccata, per poi essere distribuita ai consumatori sotto forma di *servizio energetico*. È importante sottolineare che ognuna di queste trasformazioni richiede una spesa energetica, che dipende dalla tecnologia selezionata per far avvenire la trasformazione stessa. Sottraendo dunque le diverse spese energetiche, si ottiene il surplus energetico (*energia utile*) in grado effettivamente di coprire un servizio.
Il concetto di sostenibilità è descritto dall'intersezione di tre criteri tra loro interconnessi (Fig. 3.1) [51]:

- *Prossimità.* Riguarda la localizzazione della risorsa energetica, o meglio la distanza tra questa e il suo consumatore. Un sistema energetico sostenibile dovrebbe usare le risorse più prossime alla sua area geografica.
- *Adeguatezza.* Questo criterio riguarda non solo la qualità dell'*energy carrier* rispetto al servizio energetico che dovrà ricoprire (calore, elettricità, chemical), ma anche la sua origine (direttamente prodotto da una fonte di *energia primaria*, surplus di produzione o recuperato dopo un primo utilizzo).
- *Vitalità.* Si tratta dell'abilità di una data tecnologia di restituire alla società *energia utile*. La quantità di *energia utile* che la catena della tecnologia energetica (ETC) reimmette nella società, deve superare il fabbisogno energetico dell'ETC stessa.

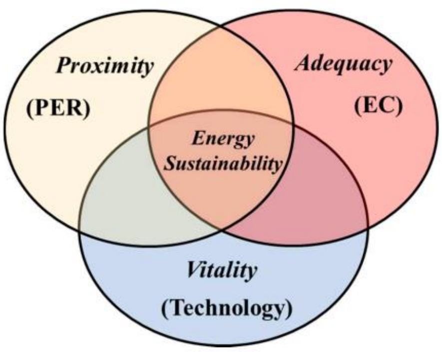

Figura 3.1: Diagramma di Venn sul nuovo paradigma della sostenibilità energetica. Figura presa da [51] con modifiche.

Considerando che ad oggi per coprire uno stesso servizio energetico sono disponibili diverse tecnologie, è nata la necessità di fornirsi di strumenti in grado di selezionare quella più adeguata. La *Life Cycle Assessment* (LCA) e l'*Energy Sustainability Analysis* (ESA) sono due metodologie altamente adatte a questo scopo. Entrambe si propongono infatti di misurare il livello di sostenibilità di una tecnologia, rispettivamente da un punto di vista di impatti ambientali ed energetico.
In particolare, l'LCA è uno strumento standardizzato (ISO 14040-44) e quantitativo, volto a valutare gli impatti ambientali e le risorse utilizzate durante il ciclo di vita di un processo/prodotto. Si parte dunque dall'acquisizione delle materie prime, passando per le fasi di produzione e utilizzo, fino alla gestione del fine vita (approccio dalla culla alla tomba). Gli impatti ambientali sono definiti come i risultati delle attività umane sulle quattro geo-componenti (litosfera, idrosfera, biosfera e atmosfera) attraverso il rilascio o il consumo di risorse. Pertanto, l'LCA identifica e quantifica l'energia e i materiali utilizzati, nonché i flussi rilasciati nell'ambiente, e i loro potenziali impatti lungo l'intero ciclo di vita, fornendo indicazioni sulla sostenibilità ambientale dei sistemi di prodotti/servizi.
Per eseguire l'LCA, è necessario eseguire quattro fasi principali:

1. Definizione dell'obiettivo e del campo di applicazione
2. Inventario del ciclo di vita (LCI)
3. Valutazione dell'impatto del ciclo di vita (LCIA)
4. Interpretazione dei risultati

La prima fase consiste nella dichiarazione dell'obiettivo e del campo di applicazione dello studio LCA. Una volta esplicitati, è possibile definire l'unità funzionale (FU). L'unità funzionale è un parametro di riferimento a cui attribuire i risultati dell'LCA. La scelta è arbitraria, ma deve essere coerente con gli obiettivi dello studio e con la funzione per cui il sistema in esame è stato progettato. Inoltre, in questa prima fase, è obbligatorio definire le condizioni al contorno del sistema: dalla culla al cancello (fase intermedia della catena analizzata) o dalla culla alla tomba (fine vita).
Anche le categorie di dati e i requisiti di qualità ad essi associati sono fondamentali, e devono essere coerenti con gli obiettivi e il campo di applicazione della LCA. Ad esempio, possono essere selezionati dati primari (rilevati direttamente in loco) o secondari (provenienti da letteratura e banche dati).
Infine, devono essere definiti i criteri di cut off per gli input e gli output: il sistema analizzato deve essere modellato in modo tale che tutti gli input e gli output al suo confine siano flussi elementari.
La seconda fase dell'LCA è l'inventario del ciclo di vita (LCI). Lo scopo è fornire, per il sistema in esame, una descrizione dettagliata e una quantificazione degli input di materie prime e combustibili, e degli output di sottoprodotti e rifiuti (solidi, liquidi e gassosi), durante il corso del suo ciclo vita. Si tratta di un rilevamento sistematico di tutti gli scambi fisici tra il sistema e l'ambiente, ed è caratterizzato da: diagrammi di flusso, raccolta di dati, criteri di allocazione e gestione del fine vita.
In particolare, l'allocazione è necessaria per i processi che producono più prodotti o coprodotti. Infatti, in questi casi, è necessario suddividere gli impatti ambientali del processo tra i vari prodotti. Si possono effettuare due tipi di allocazione: fisica ed economica. La prima cerca di dividere gli impatti ambientali tra i prodotti in funzione della loro quantità (ad esempio, la massa). La seconda, invece, distribuisce gli impatti in base al loro valore economico.
Pertanto, attraverso l'LCI, si ottiene una stima fisica degli impatti generati da un'attività. Tuttavia, sia il consumo di risorse che le emissioni di rifiuti influenzano l'ambiente, generando una variazione del suo status quo. A questo proposito, la LCIA mira a valutare l'entità e la significatività dei potenziali impatti ambientali di un processo/prodotto.

In particolare, i dati ottenuti dall'LCI vengono assegnati alle cosiddette "categorie di impatto", in base alla loro capacità di contribuire a diverse problematiche ambientali. Esempi di categorie di impatto sono: potenziale di riscaldamento globale (GWP), riduzione dell'ozono, acidificazione, eutrofizzazione, smog fotochimico, tra gli altri. Dopo questa prima classificazione, l'impatto di ogni emissione o consumo di risorse viene modellato quantitativamente, in base al meccanismo ambientale, utilizzando un "fattore di caratterizzazione" adeguato. Quest'ultimo è necessario per esprimere un flusso in entrata/uscita nell'unità della categoria di impatto a cui fa riferimento. Ad esempio, le emissioni di gas serra sono espresse in kg di CO_2 equivalente e contribuiscono alla categoria d'impatto "cambiamento climatico", determinando un aumento generale della temperatura terrestre.
Quella appena descritta è la LCIA condotta a livello di midpoint. Tuttavia, l'analisi può essere estesa al livello endpoint che, utilizzando fattori di caratterizzazione diversi, fornisce il danno associato agli impatti (per "danno" si intende un cambiamento effettivo e quasi permanente di un sistema, come conseguenza di un'attività antropica). Le cosiddette "aree di protezione" (AoP) sono i contesti in cui il danno, generato da un impatto, viene valutato qualitativamente e quantitativamente. Le AoP includono: salute umana, ecosistema e risorse naturali. A titolo di esempio, le emissioni di gas serra condizionano il cambiamento climatico generando un aumento della temperatura, che si ripercuote sull'ecosistema.
L'ultima fase dell'LCA è l'interpretazione dei risultati, in cui i risultati della fase di inventario o della valutazione d'impatto, vengono combinati in modo coerente con l'obiettivo e l'ambito di applicazione precedentemente definiti, al fine di raggiungere conclusioni e raccomandazioni finali. Oltre alle conclusioni e alle raccomandazioni, possono/devono essere eseguiti controlli di coerenza e completezza, analisi del contributo, della sensibilità e dell'incertezza.
Come anticipato, l'LCA non è l'unico strumento utilizzabile nella valutazione della sostenibilità di tecnologie. A tal proposito, l'analisi di sostenibilità energetica (ESA) è una metodologia che considera l'intera traiettoria energetica, dalla fonte di energia all'*energia utile*. Quest'ultima, come anticipato, viene utilizzata come criterio per confrontare le prestazioni di diverse tecnologie volte alla produzione energetica.
Pertanto, come avviene nell'LCA, anche in questo tipo di analisi è fondamentale la selezione di condizioni al contorno appropriate. In particolare, la dimensione di riferimento di questa analisi è la sfera antropologica.
Una tecnologia valida (o una tecnologia energeticamente sostenibile) dovrebbe essere in grado di produrre un surplus energetico (*energia utile*) in grado di alimentare la società, dopo aver scontato i costi energetici diretti e indiretti del processo stesso. Per comprendere meglio il concetto di questa analisi, si riportano di seguito alcune definizioni utili:

- *Energia primaria*. È l'energia incorporata in una risorsa primaria, cioè una risorsa direttamente estratta dall'ambiente naturale (ad esempio, petrolio greggio, sole...). Quindi questa energia, estratta dalla sfera biofisica, è "gratuita". Tuttavia, per essere utilizzata, deve essere convertita in un vettore energetico adeguato (ad esempio, l'energia solare, cioè un'energia primaria, per essere sfruttata, deve essere convertita in elettricità, che in questo caso è il vettore energetico. Per effettuare questa conversione è necessaria una spesa energetica dovuta all'inevitabile inefficienza delle tecnologie impiegate alla conversione stessa).
- *Energia prodotta*. È l'energia accessibile, cioè la massima energia ottenibile da un processo (una frazione di quella disponibile), considerando il limite di efficienza termodinamica del processo utilizzato, in funzione delle condizioni operative.
- *Energia diretta*. È la spesa energetica di un processo in termini di consumo di elettricità e calore.
- *Energia indiretta*. Include tutti i requisiti energetici aggiuntivi della tecnologia. Si tratta della quota di energia sottratta alla società, a livello di antroposfera, per fornire i flussi di

materiali, prodotti chimici e combustibili e altri servizi ausiliari aggiuntivi. È la somma di diversi contributi, riassunti nella Tabella 3.2.

- *Energia incorporata*. È l'energia totale spesa per ottenere un prodotto, compreso un *energy carrier*. Può essere espressa come *Cumulative Energy Demand* (CED) o come *Gross Energy Demand* (GER). Il primo, a differenza del secondo, tiene conto anche del contenuto energetico dell'*energy carrier*. Pertanto, il CED è la spesa energetica totale sottratta sia alla sfera antropologica che a quella biofisica (includendo sia le risorse rinnovabili che quelle non rinnovabili). Al contrario, il GER è la somma dei vettori energetici spesi per ottenere un prodotto. Quindi, quest'ultimo dipende dalle spese energetiche a livello antropologico, che sono funzione dello stato dell'arte della tecnologia. Tuttavia, non considera l'energia contenuta nel vettore energetico.

Tabella 3.2: Contributi dell'*energia indiretta* [52].

$E_{ind,i}$	**Descrizione**
E_{chem}	Energia indiretta utilizzata per produrre i chemicals del processo
E_{mat}	Energia indiretta utilizzata per produrre i materiali del processo
$E_{ind\ to\ produce\ Edir}$	Energia indiretta utilizzata per produrre e usare l'energia diretta del processo
E_{maint}	Energia indiretta utilizzata per scopi manutentivi
E_{labor}	Energia indiretta utilizzata per sostenere il lavoro umano
E_{constr}	Energia indiretta utilizzata per scopi di costruzione
E_{decomm}	Energia indiretta utilizzati per scopi di dismissione
E_{amort}	Energia indiretta allocata per l'ammortamento dei materiali e dei prodotti chimici dell'impianto sostitutivo

Ai fini dell'analisi di sostenibilità che si intende effettuare, è obbligatorio indagare il termine di E_{amort}. Infatti, questo contributo rappresenta una differenza fondamentale tra LCA e ESA. L'ammortamento è necessario per tenere conto della possibilità di riprodurre la tecnologia oggetto dell'analisi (anche in termini energetici). Questo concetto è uno dei pilastri principali del concetto stesso di sostenibilità: una tecnologia, per essere sostenibile, deve essere *vitale*, cioè riproducibile, al fine di mantenere e garantire la copertura dei servizi energetici in ambito antropologico.

Pertanto, una tecnologia energetica deve essere in grado di produrre una quantità di energia sufficiente sia per sostenere le proprie necessità operative sia per la propria riproduzione. La parte restante è quella effettivamente in grado di alimentare la civiltà in una forma appropriata (*energia utile*). In sintesi, la Figura 3.2 mostra la traiettoria dell'energia dalla sua forma primaria a quella utile.

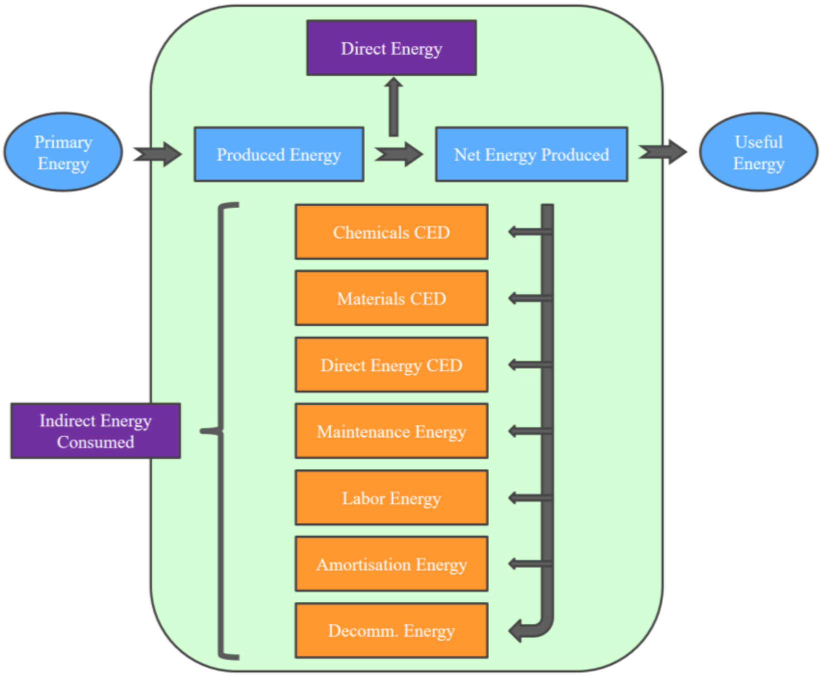

Figura 3.2: Traiettoria dell'energia: dalla primaria all'utile.

L'ESA è condotta a due livelli:

i. A breve termine: si valuta l'indice di sostenibilità energetica (ESI) per stabilire se l'energia prodotta è in grado di coprire le spese energetiche dirette necessarie al funzionamento della tecnologia.
ii. A lungo termine: si valutano il ritorno sull'investimento energetico (EROI) e il tempo di ritorno energetico (EPT), al fine di tenere conto di tutte le quote energetiche indirette.

L'EPT indica il lasso di tempo che una particolare tecnologia richiede per compensare l'energia indiretta spesa per la produzione di materiali e per la sua costruzione, insieme ad altri importanti investimenti energetici.
L'EROI, invece, è una misura della redditività energetica delle fonti e delle tecnologie energetiche. Infatti, mette in relazione la quantità di *energia netta* prodotta, con l'energia totale investita. In letteratura si trovano diverse espressioni per la formula dell'EROI, pertanto è obbligatorio specificare quella scelta per l'analisi specifica condotta.
Le equazioni 3.3-3.7 riassumono le formule adottate per il calcolo dei parametri appena discussi.

$$E_{net} = E_{prod} - E_{dir} \tag{3.3}$$

$$E_{useful} = E_{net} - E_{ind} \tag{3.4}$$

$$ESI = \frac{E_{prod}}{E_{dir}} \tag{3.5}$$

$$EROI = \frac{E_{net}}{E_{ind}} \tag{3.6}$$

$$EPT = \frac{E_{ind}}{E_{net}/lifespan} \tag{3.7}$$

A valle di quanto esposto, il primo passo obbligatorio di un'analisi di sostenibilità (sia ESA che LCA) è la definizione degli obiettivi e del campo di applicazione. Per il lavoro di tesi svolto,

l'obiettivo dell'LCA è valutare l'impronta ambientale del FLNG, attraverso uno studio dettagliato delle operazioni unitarie, delle attrezzature necessarie e degli scambi chiave (input/output) con la biosfera/tecnosfera per il suo funzionamento, durante la sua vita utile. Inoltre, si intende confrontare quanto ottenuto per l'FLNG (rispetto la fase di produzione e di trattamento), con i processi convenzionali dell'LNG. In particolare, con questo paragone, si mira a stabilire se l'FLNG può essere competitivo come opzione. La stessa analisi verrà poi estesa a tutta la catena, al fine di condurre un paragone sia con la catena di approvvigionamento relativa all'LNG che con quella del NG. In questo modo, verranno evidenziate le condizioni in cui un'opzione è più favorevole rispetto che le altre, in base alla distanza di trasporto selezionata e all'impronta ambientale che ne consegue. Allo stesso modo, l'ESA cerca di offrire una prospettiva di sostenibilità energetica della catena di approvvigionamento dell'FLNG, per determinare se questa può effettivamente fornire energia utile alla società (e in quale proporzione rispetto all'investimento), oltre a determinare il tempo di ritorno energetico.
A seconda dell'analisi effettuata, vengono considerati diversi confini. Per il primo caso, in cui sono esaminati i processi di produzione e trattamento del FLNG e dell'LNG, il confine comprende le operazioni di estrazione, trattamento e liquefazione. Per l'intera catena di approvvigionamento fino all'utente finale, i confini sono estesi per includere le operazioni di trasporto, rigassificazione e distribuzione. L'unità funzionale per l'analisi è 1 Sm^3 di NG.
Una volta definiti gli obiettivi e il campo di applicazione, è possibile svolgere l'LCI. In particolare, la fase d'inventario è stata svolta combinando dati primari e secondari (ottenuti dal database di *Ecoinvent v3.9 cutoff* utilizzando il software *Activity Browser*).
La piattaforma FLNG Coral Sul, è stata selezionata come caso studio. Quest'imbarcazione opera a 200 km dalle coste del Mozambico ed è progettata per sostenere un carico produttivo di c. 3,4 mtpa. Tuttavia, come noto da letteratura, questo genere di impianti, non sono in grado di assicurare una produzione continuativa al pieno delle loro efficienze. Per tenere conto delle suddette inefficienze, è stato dunque introdotto il parametro *Activity Level*, dato dal contributo di due fattori: il *load factor* (rapporto tra produzione effettiva in un determinato anno e la capacità di targa) e il *fattore di utilizzo* (rapporto tra la produzione effettiva e la produzione massima potenziale). In particolare, l'ultimo, tiene conto delle interruzioni programmate e non, dovute per esempio a situazioni di emergenza o eventi manutentivi. È per questo che, per la piattaforma galleggiante, sono state analizzate due diverse casistiche. La prima, esamina il caso ideale, per il quale si è considerato un Activity Level del 100%. La seconda rappresenta uno scenario più realistico per il quale, considerando i valori medi di *load* e *utilization factor* per questo tipo di piattaforme (Fig. 4.4), si è assunto un *Activity Level* del 70%.
Infine, per la fase di trasporto, è stata stimata una tratta percorsa dall'LNG carrier di c. 10.000 km. Questa distanza è stata simulata partendo dal bacino di Rovuma (Mozambico), fino ad arrivare al terminal LNG situato a Panigaglia (Italia). È stata inoltre assunta una distanza di 300 km per il trasporto interno di NG attraverso i gasdotti, considerando le lunghezze medie di questi all'interno della penisola Italiana.
Per compilare l'inventario di Coral Sul sono state utilizzate diverse fonti di letteratura (comprendenti dati primari e secondari), raccolte da diversi rapporti e da materiale disponibile. I dati per la piattaforma FLNG sono stati poi confrontati con dati secondari medi rappresentativi presenti nei database degli inventari del ciclo di vita (LCI). In altre parole, per i processi di produzione e trattamento dell'LNG e del NG (e le relative catene di approvvigionamento), i dati necessari per eseguire l'ESA e l'LCA sono stati ricavati da banche dati già disponibili.
Per quanto riguarda l'FLNG, i dati non disponibili dalla letteratura, sono stati ricavati effettuando delle stime sulle unità e attrezzature di interesse installate sulla piattaforma, sulla base del layout generale di questo tipo di impianti. Le dimensioni di riferimento per ogni unità, necessaria per il trattamento dei fluidi grezzi dei giacimenti (Fig. 4.3), sono state stimate in base alla produzione dichiarata e alle specifiche dei fluidi estratti dal giacimento. Dunque,

utilizzando delle equazioni di progettazione di base, è stato possibile stimare i diametri, le altezze e di conseguenza i volumi e i pesi di interesse. Per semplificare l'approccio, colonne, serbatoi, scambiatori di calore, pompe e compressori sono stati generalmente assunti come gusci cilindrici con fondo sferico. I due materiali considerati per la costruzione della piattaforma sono stati l'acciaio, e l'alluminio (per le applicazioni criogeniche).
Le Tabelle 4.11-14, riassumono tutti i risultati ottenuti dalla fase di inventario, che verranno di conseguenza utilizzati per eseguire le fasi successive dell'LCA e dell'ESA di Coral Sul.
In primo luogo, è stata svolta l'LCA. Per la valutazione dell'impatto sono stati adottati il CED e il metodo CML v4.8. Inoltre, al fine di analizzare lo scenario più conservativo, per la struttura FLNG è stato considerato un *Activity Level* del 100%. In particolare, la prima analisi è stata condotta al fine di paragonare la variazione del CED e delle diverse categorie di impatto, quando si considera non solo la fase di produzione e trattamento, ma anche l'intera la catena dell'FLNG (Fig.4.5).

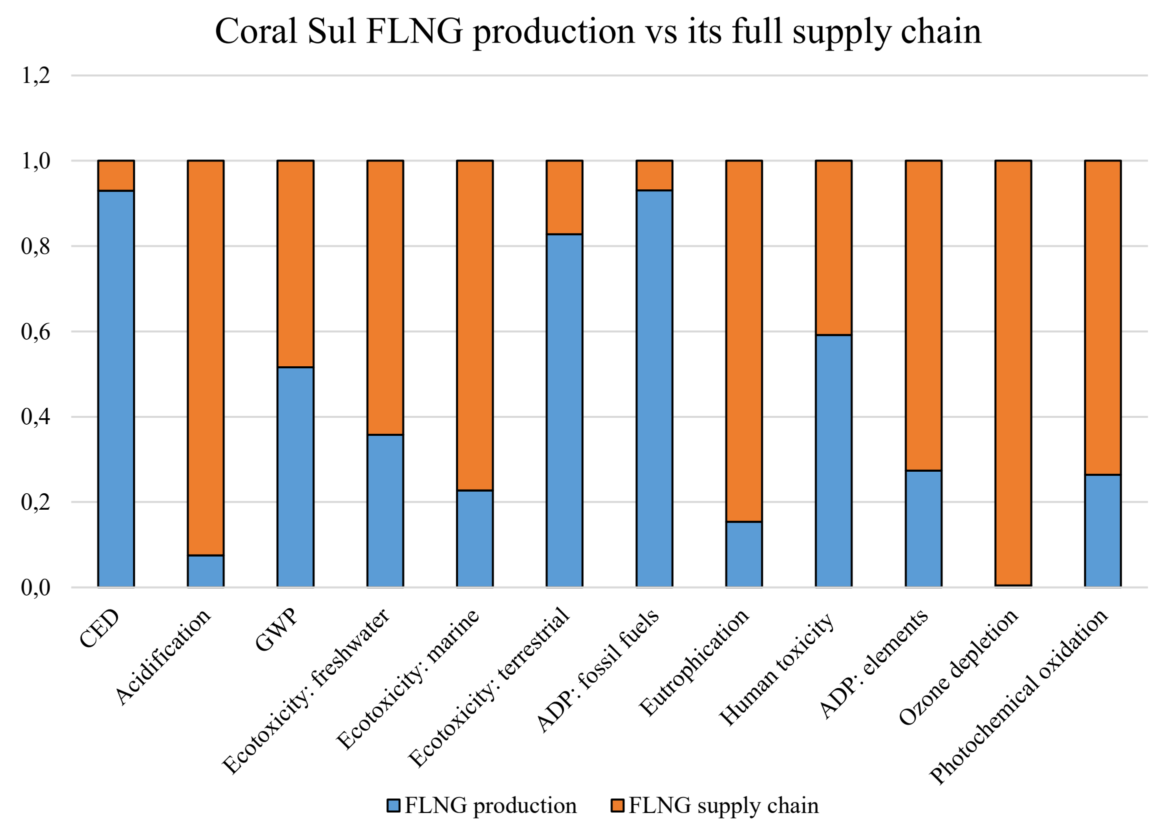

Figura 4.5: Confronto dei risultati LCA: produzione FLNG vs catena correlata.

In secondo luogo, è stata paragonata, in accordo con quanto definito negli obiettivi, la fase di produzione e trattamento eseguita dall'FLNG con quella eseguita dai convenzionali processi LNG. A tal fine, sono stati selezionati due processi LNG: quello globale (come caso di riferimento più generale) e quello che descrive la produzione di LNG specifica per la Malesia. Quest'ultimo set di dati è stato scelto in quanto include, nel suo mix di produzione, anche quello proveniente dagli impianti FLNG (Petronas I e II). Per questa analisi, il confine va dall'estrazione alla liquefazione del NG. I risultati sono mostrati nella Fig. 4.6, dove ogni valore è normalizzato rispetto alla piattaforma FLNG utilizzata come caso di studio.

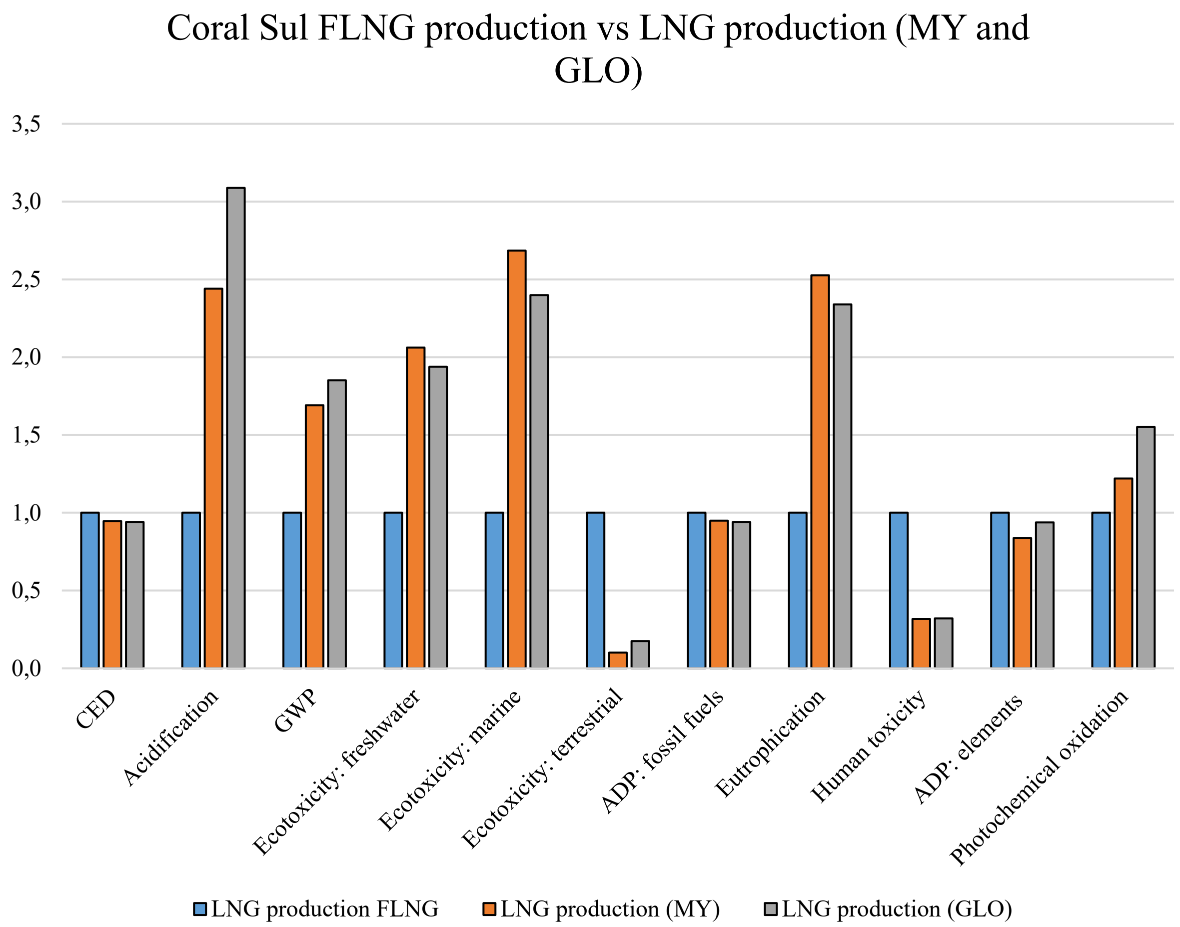

Figura 4.6: Confronto dei risultati LCA: produzione LNG (MY e GLO) vs produzione FLNG.

Come anticipato, al giorno d'oggi circa il 70% del NG viene trasportato attraverso i gasdotti, mentre la parte restante attraverso la sua forma liquefatta. Pertanto, il confronto tra FLNG e le catene di approvvigionamento convenzionali del NG e LNG (Tab.4.18-19), è risultato obbligatorio ai fini dello studio svolto in questa tesi. In questo caso, i confini scelti per l'analisi si estendono dalla produzione alla distribuzione del NG attraverso la rete nazionale.
Come per le catene dell'FLNG/LNG, per la catena di approvvigionamento del NG è stata stimata una lunghezza dei gasdotti offshore e onshore rispettivamente di 580 km e 9420 km, per simulare il trasporto dal bacino di Rovuma al terminal di Panigaglia. I risultati sono mostrati nella Fig. 4.7, dove ogni valore è normalizzato rispetto alla piattaforma FLNG utilizzata come caso di studio.

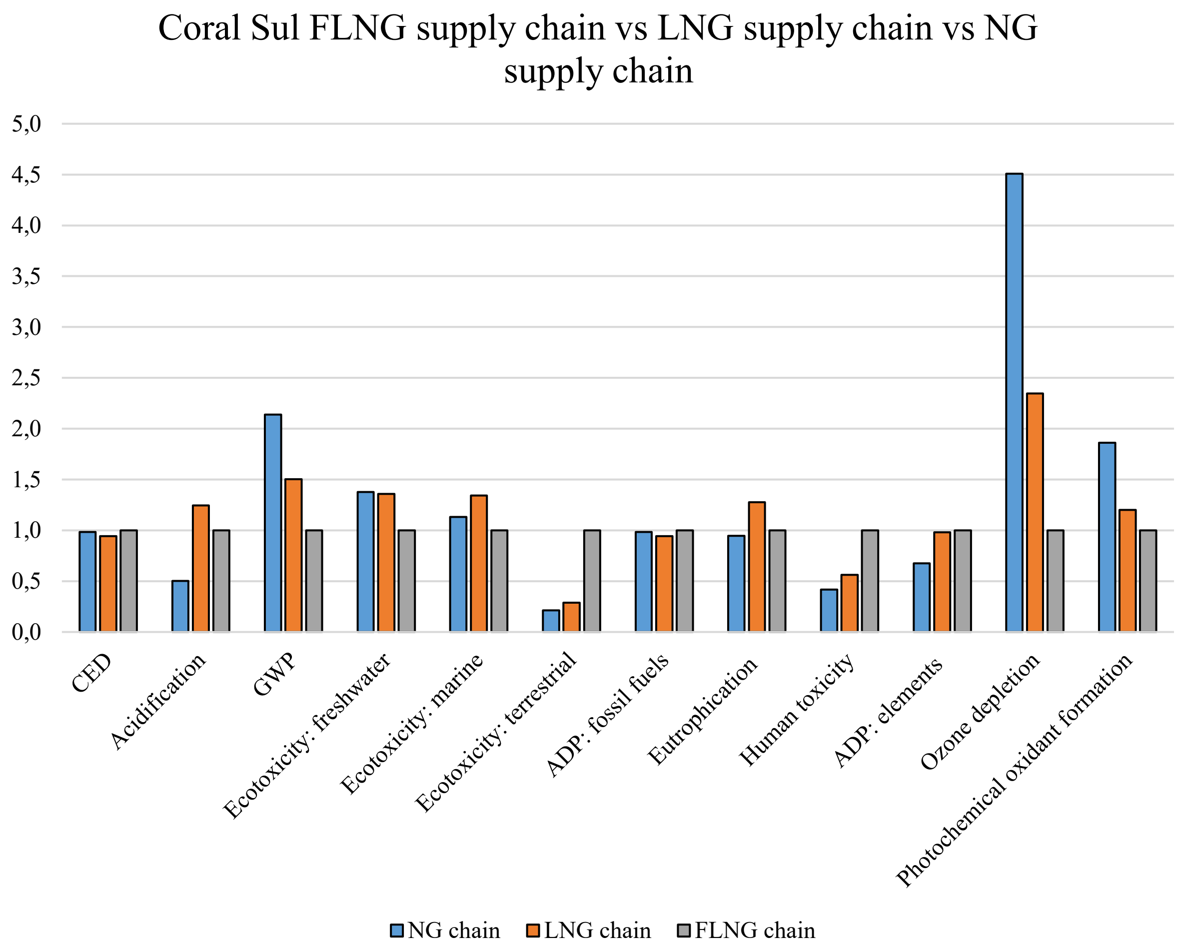

Figura 4.7: Confronto dei risultati LCA relativi alle tre catene di approvvigionamento: NG, LNG e FLNG.

Così come l'LCA, l'ESA è una metodologia utilizzata per indagare la sostenibilità di un processo ma, in questo caso, da una prospettiva energetica. Come anticipato, l'ESA si basa sul calcolo di tre parametri principali, che possono aiutare a caratterizzare la sostenibilità energetica di una specifica tecnologia a due diversi livelli temporali: a breve termine (ESI) e a lungo termine (EROI e EPT). Nel presente studio, le prestazioni della piattaforma FLNG sono confrontate, ancora una volta con le tecnologie convenzionali di produzione di LNG e NG e con la loro catena di approvvigionamento.

Come prima analisi, è stata indagata la fase di produzione e trattamento eseguita da Coral Sul lungo il suo ciclo di vita, considerando un livello di attività del 100%. Pertanto, i confini spaziali di questa prima ESA vanno dall'estrazione alla liquefazione.

La Tab.4.20 riassume le fonti di energia primarie coinvolte in questa analisi e la conseguente valutazione dei flussi di energia netta e utile (Eq.3.3-3.4), mentre la Tab.4.22 riporta i risultati ottenuti.

Tabella 4.22: Risultati ESA relativi alla produzione di Coral Sul, considerando un *Activity Level* del 100%.

ESA FLNG (Activity level of 100%)	
ESI [-]	24,70
EROI [-]	54,46

EPT [years]	0,46

Apportando le opportune modifiche ad alcuni dei parametri elencati in Tab.4.20, conseguenti alla minor produzione dell'FLNG, è stata svolta una seconda ESA per un *Activity Level* del 70%, prendendo così in esame uno scenario più realistico. I risultati ottenuti sono riportati in Tab.4.24.

Tabella 4.24: Risultati ESA relativi alla produzione di Coral Sul, considerando un *Activity Level* del 70%.

ESA FLNG (Activity level of 70%)	
ESI [-]	24,70
EROI [-]	39,0
EPT [years]	0,60

Così come svolto per l'LCA, anche l'ESA si è posta l'obiettivo di indagare l'intera catena di approvvigionamento della piattaforma FLNG (a tal fine è stato considerato un *Activity Level* del 70%). Le spese energetiche dirette e indirette di ogni fase della catena di approvvigionamento, necessarie per eseguire il calcolo dell'ESI, dell'EROI e dell'EPT, sono state riportate nella Tab.4.25. Dalla stessa tabella, è interessante notare che il consumo energetico dell'intera filiera corrisponde all'11,3% del contenuto energetico del NG iniziale, ovvero dell'energia primaria. Come previsto, la fase che richiede più energia è quella del trattamento, probabilmente a causa del processo di liquefazione intensivo. Questa percentuale risulta leggermente inferiore rispetto ai valori che si possono trovare in letteratura [73] per la filiera convenzionale dell'LNG, che si aggirano intorno al 20%. In particolare, secondo [73] la liquefazione è la fase della catena che richiede più energia, consumando dal 5 al 15% dell'LNG che attraversa il processo (Fig. 4.12). Questa differenza tra la piattaforma FLNG studiata e i processi di LNG convenzionali, può essere giustificata dal minore consumo di energia diretta della prima. In particolare, per la costruzione di Coral Sul sono state adottate tecniche specifiche per minimizzare il più possibile l'energia necessaria per la liquefazione che, come precisato, ha il più alto potenziale di riduzione della domanda energetica [74].
La Tab.4.26 mostra i risultati ottenuti per l'ESA della filiera FLNG nelle condizioni ipotizzate.

Tabella 4.26: Risultati ESA relativi alla catena di approvvigionamento correlata a Coral Sul, considerando un *Activity Level* del 70%.

ESA FLNG supply chain	
ESI [-]	11,20
EROI [-]	19,20
EPT [years]	1,30

Raccogliendo tutti i dati ottenuti sia per l'LCA che per l'ESA, è possibile trarre delle conclusioni rispetto gli obiettivi della tesi originariamente imposti. Innanzitutto si può evidenziare che, combinando dati primari e secondari (ottenuti dal database *Ecoinvent v3.9 cutoff*), i materiali impiegati per l'impianto galleggiante sono risultati essere superiori dell'11% rispetto alle 220.000 tonnellate dichiarate da Eni [64]. Questi materiali aggiuntivi calcolati, serviranno a coprire eventuali spese per i materiali, come la manutenzione o le sostituzioni, lungo il ciclo di

vita della struttura galleggiante. Oltre questi materiali, ulteriori emissioni solide/gassose/liquide sono state valutate in accordo con [68].
Per la valutazione degli impatti ambientali è stata utilizzata la tecnica LCA. Una prima analisi è stata condotta sulla piattaforma FLNG e sulla sua catena di approvvigionamento. Come previsto, sono stati registrati valori più elevati per ogni categoria di impatto, dovuti a un aumento degli scambi con la tecnosfera e la biosfera, quando è stata considerata l'intera catena. In particolare, il trasporto attraverso la metaniera ha portato a un notevole aumento dell'*acidificazione* e dell'*eutrofizzazione*. La *riduzione dell'ozono* è risultata quasi nulla per l'impianto galleggiante: il suo processo di liquefazione impiega etano e butano, invece dei composti refrigeranti più impattanti normalmente utilizzati. Tuttavia, questi refrigeranti vengono sfruttati in altre fasi della filiera (ad esempio, il trasporto nei gasdotti), portando a valori di *riduzione dell'ozono* più elevati. D'altra parte, scontando l'HHV (potere calorifico superiore) dell'LNG prodotto (cioè 40,5 MJ/m^3) sui valori del CED, si è notato che il GER ottenuto dipende quasi interamente dalla fase di produzione che, quindi, è risultata essere la fase più impegnativa dal punto di vista energetico. Mentre, scontando la stessa quantità sull'*ADP fossile*, si è visto che questa categoria dipende fortemente sia dalla produzione di FLNG sia dall'intera catena. Lo stesso, in termini di contributi delle diverse fasi, si può osservare per il GWP. Infine, il processo di rigassificazione è risultato responsabile dei valori più elevati dell'*ADP degli elementi* raggiunti.
Un altro obiettivo della tesi è stato il confronto tra il processo di produzione FLNG e quello LNG convenzionale. L'LCA ha mostrato che si ottengono valori simili di GER (considerando i diversi HHV associati, pari a 40 MJ/m^3 per l'LNG), quindi, dal punto di vista della domanda di energia incorporata, non sono stati evidenziati vantaggi nell'utilizzo di un'opzione o dell'altra. Lo stesso è stato notato per entrambi gli *ADP* (*fossili* ed *elementi*). Tuttavia, l'impianto galleggiante è risultato essere l'opzione migliore se si considerano tutte le altre categorie di impatto, ad eccezione dell'*ecotossicità terrestre* e della *tossicità umana*. I valori elevati di queste due categorie dipendono strettamente dall'elevata quantità di acciaio impiegata nella piattaforma FLNG. Inoltre, tra i risultati mostrati, è stato evidenziato che il GWP associato all'impianto galleggiante è quasi due volte inferiore rispetto ai processi LNG convenzionali. Come già detto, secondo [53] la domanda di energia di Coral Sul, grazie all'alta efficienza delle tecnologie impiegate, è molto più bassa rispetto ai processi LNG disponibili sul mercato. Di conseguenza, il GWP è necessariamente inferiore a causa di una minore quantità di emissioni di gas serra, il che rappresenta un vantaggio cruciale dell'impianto FLNG.
Infine, su una distanza di trasporto di circa 10.000 km, sono state analizzate le tre principali catene di approvvigionamento: FLNG, LNG e NG. Innanzitutto, è stato evidenziato che il CED e l'*ADP fossile* (entrambi scontati dell''HHV del rispettivo combustibile prodotto) sono simili per le tre catene. Inoltre, considerando i risultati per ogni categoria di impatto, si è notato che non esiste un chiaro vantaggio nello sfruttamento di una catena rispetto all'altra, poiché a seconda della categoria cambia l'opzione favorevole. Tuttavia, considerando gli attuali sforzi della società per muoversi verso uno scenario di emissioni nette zero, il GWP può essere scelto come criterio di selezione tra le catene. A questo proposito, la Fig. 4.7 mostra che l'FLNG, per il caso di studio analizzato, rappresenta l'opzione migliore poiché il suo valore è 1,5 e 2 volte inferiore rispetto alle catene LNG e NG, rispettivamente. Tuttavia, come rappresentato nella Fig. 4.8, il GWP varia in funzione della distanza percorsa, soprattutto a causa delle diverse emissioni fuggitive di metano: per distanze superiori ai 2500 km si verifica un trade-off con i gasdotti. In altri termini, attraverso lo studio effettuato, sono state valutate le emissioni indirette relative a 1 Sm^3 di NG prodotto. Per tenere conto delle emissioni dirette dovute all'utilizzo della stessa quantità, è stata considerata la combustione del NG. A tal fine è stato utilizzato un fattore di emissione di 1,92 kg CO_2/Sm^3. La Fig. 4.9 mostra il contributo delle emissioni indirette rispetto a quelle dirette, in termini di GWP. Come previsto, il GWP totale aumenta con la

distanza percorsa. È stato osservato che, per le distanze più piccole, le emissioni indirette del FLNG e dell'LNG coprono una percentuale maggiore del GWP totale rispetto alle catene di NG. Tuttavia, quando il trasporto incrementa, queste percentuali rimangono circa costanti: passano da circa il 23% al 27% e da circa il 18% al 22%, rispettivamente per l'LNG e il FLNG. Al contrario, un aumento più evidente è stato notato per le catene NG, dove il contributo delle emissioni indirette aumenta fortemente con la distanza percorsa. Infatti, si passa da circa il 12% al 44% e da circa il 12% al 42%, rispettivamente per il caso onshore e offshore. Pertanto, considerando il contributo delle emissioni indirette valutato con quest'ultima analisi, si dimostra l'importanza di valutare gli impatti ambientali delle catene di approvvigionamento.
Per indagare la sostenibilità dei processi da un punto di vista energetico, è stata applicata la metodologia ESA. In primo luogo, sono state esplorate le fasi di produzione e trattamento di Coral Sul, sia per un *Activity Level* del 100% che per uno del 70%. Quest'ultimo, in particolare, mirava a rappresentare uno scenario più realistico, che considerava le possibili interruzioni che si verificano normalmente in questi impianti. Come previsto per un livello di attività più basso, l'EROI è diminuito (passando da 54,46 a 39,0) poiché l'energia netta, che ha il contributo più forte sull'indice, è diminuita a causa della minore produzione. L'ESI, invece, è rimasto costante a 24,7 nei due scenari, poiché l'energia prodotta e quella diretta sono diminuite proporzionalmente. Infine, l'EPT è aumentato, passando da 0,46 a 0,60 anni: è necessario più tempo per compensare gli investimenti energetici iniziali.
Considerando un livello di attività del 70%, è stata valutata l'intera catena di approvvigionamento della piattaforma FLNG. Come previsto, l'aggiunta di nuove fasi (cioè dell'aumento del dispendio energetico) ha portato a valori più bassi di ESI ed EROI e a valori più alti di EPT, che hanno raggiunto valori di 11,20, 19,20 e 1,3 anni, rispettivamente. La Tab. 4.25 mostra il contributo di ogni fase della catena in termini di percentuale di energia primaria. Complessivamente, risulta che il consumo energetico dell'intera filiera corrisponde all'11,3% del contenuto energetico contenuto nel NG estratto. La fase più impegnativa dal punto di vista energetico è quella del trattamento, a causa del processo di liquefazione ad alta intensità energetica. Questa percentuale è risultata leggermente inferiore rispetto ai valori trovati in letteratura per la filiera convenzionale dell'LNG, che si aggirano intorno al 20%. Ciò è probabilmente giustificato dal minor consumo energetico diretto richiesto dalle tecniche adottate da Coral, che sono state selezionate appositamente per minimizzare il più possibile l'energia necessaria alla liquefazione.
Infine, la tesi mirava a confrontare la catena di approvvigionamento dell'FLNG con quelle convenzionali di LNG e NG. [75] ha fornito una revisione della letteratura e un'armonizzazione dei valori EROI dei principali vettori energetici. La valutazione dell'EROI è una metrica popolare per valutare la redditività dei processi di estrazione dell'energia e, pertanto, può essere utilizzata come strategia di confronto. Nonostante le differenze metodologiche nel calcolo dell'EROI, la valutazione effettuata ha mostrato che l'EROI trovato per l'impianto FLNG (cioè 8,9) è leggermente superiore rispetto ai processi di produzione convenzionali LNG, caratterizzati da un valore EROI di 6,3. D'altra parte, per la catena di approvvigionamento dell'FLNG è stato ottenuto un EROI di 7,3. Questo valore è risultato essere, secondo [75], perfettamente in linea con i valori di EROI associati alla filiera dell'NG convenzionale, che si collocano nell'intervallo 5-8. Pertanto, da un punto di vista energetico, considerando i valori di EROI ottenuti, non sono stati evidenziati chiari vantaggi nello sfruttamento di una filiera piuttosto che di un'altra. Tuttavia, per la produzione e il trattamento dell'LNG, l'opzione FLNG è risultata essere più vantaggiosa rispetto ai processi di LNG convenzionali, in quanto il suo EROI è superiore di circa il 40%.

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1. Introduction

1.1 Motivation

In the current energy scenario, natural gas (NG) represents at least 20% of the global primary energy consumption and more than 30% of the overall fossil consumption. After the 2020 pandemic, amid a first reduction in the demand of c. 3%, the growth of the NG sector surpassed other fossil fuels reaching up to 5%. Indeed, NG has been envisaged as an enabler for the transition towards a low greenhouse gas (GHG) emissions economy, due to its improved environmental performance compared to other fossil feedstock. Nowadays, NG is transported mainly via two options, which involve different supply chains. About the 70% of NG is transported in its gaseous form through pipelines, whereas the remaining part as liquefied natural gas (LNG). Moreover, due to demand increase, in the last years stranded NG reservoirs are gaining attention. The emerging Floating Liquefied Natural Gas (FLNG) facilities are playing a fundamental role in the exploitation of these abundant offshore resources. Furthermore, these technologies represent an answer to the current geopolitical constraints, providing flexibility to the supply chain and likely improving the security of the energy supply. Since the environmental impacts of full supply chains are gaining relevance for the current climate change mitigation goals, a sustainability analysis of the different NG supply chains results to be mandatory. In particular, the thesis will shed light on the arising FLNG facilities.

1.2 Objectives

Establishing the environmental impacts of supply chains results to be mandatory for moving towards a more sustainable society, meeting the current climate change mitigation goals.
In particular, the different NG supply chains are investigated.
In the first instance, this thesis aims to compare the conventional production and processing technologies (i.e., NG and LNG facilities) with the emerging FLNG one, in terms of engineering requirements of each of them. Specifically, the *Coral Sul* facility is evaluated in detail as a model case study for the generation of an accurate inventory of the main exchanges with the technosphere and biosphere, considering all life stages and production patterns reported in the literature for this type of facilities. The inventory phase was carried out by combining primary and secondary data (obtained from the *Ecoinvent v3.9 cutoff* database).
Once the upstream phase was investigated, the analysis were extended to the full supply chains, comparing in this way the current available options for transporting NG (i.e., NG, LNG, and FLNG).
The environmental impact was evaluated through the life cycle assessment (LCA) technique, and the energy performance through the energy sustainability analysis (ESA). For these, dedicated datasets were generated using the Activity Browser of the python *brightway2* framework, and 1 Sm^3 of NG is used as the functional unit (FU).
The LCA impact assessment phase was conducted using the CED and CML v4.8 2016 methods.

1.3 World energy mix: a general overview

With the current global population growth rate and the high per capita energy consumption, the overall energy demand is projected to rapidly increase. Indeed, primary energy use in 2021 (595.15 EJ) was 1.3% above 2019 levels. The increase was driven by emerging economies, which increased by 13 EJ, with China expanding by 10 EJ [3]. To meet this demand, different forms of energy resources are present on our planet and they differ from each other as function of several factors such as availability, cost, efficiency (with respect to the final use), and environmental impacts, among others.

Currently, in the so-called *petroleum era*, most of anthropogenic energy services are covered by fossil fuels (oil, coal and natural gas) that result to be the most employed raw materials not only in the energetic area but also in the material one. As demonstration, according to [1] fossil fuels account for an estimated 81% of global energy consumption in 2022. Furthermore, there are several key supply chains that still heavily depend on fossil feedstock. Ammonia, for example, is one of the largest produced commodity chemicals and its production (that sustains the food supply chain and consequently the demographic growth) mainly depends on methane, thus on natural gas (NG).
Fossil fuels are limited resources, therefore, intrinsically not renewable (their generation time exceeds the human time windows for several orders of magnitude) and they are the result of several natural (biogeochemical) degradation and conversion processes dating back to millions of years. Following the reports, the depletion time for these resources is estimated to be about 100 years (Fig.1.1) [2].

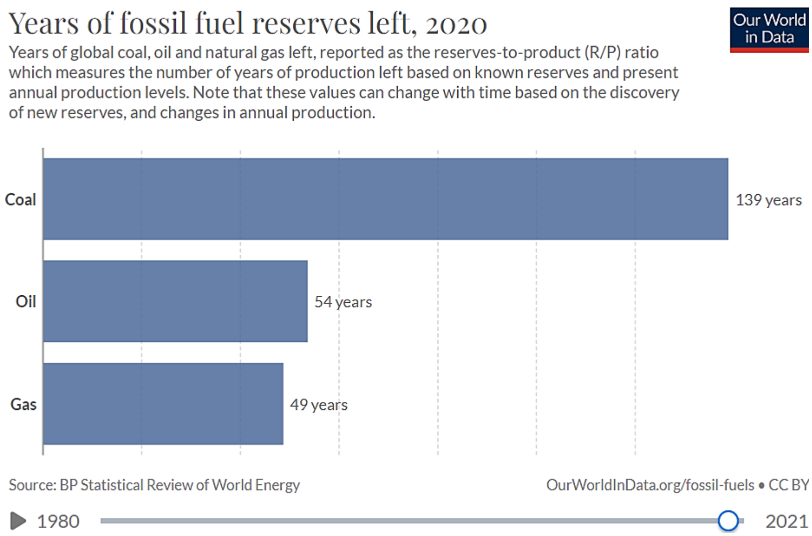

Figure 1.1: Years of fossil fuel reserves left, 2020. Figure taken from [2] with modifications.

The utilization of fossil fuels has substantial environmental impacts that have been linked to the observable climate change phenomena and, consequently, there is an urgent need to reduce their application. Hence, different strategies are being suggested and implemented for the energy transition. The main interest is to transform socio-techno-economic systems that are constructed around the exploitation of coal, petroleum and NG and migrate towards rational use of energy and the exploitation of energy sources with less environmental impacts.
Among the renewable energy sources, wind, sun, water have been largely studied. Nevertheless, nowadays the available technologies are not sufficiently developed for completely replacing fossil fuels but research is pushing for them, and their utilization is growing years by years (Fig.1.2) [4].

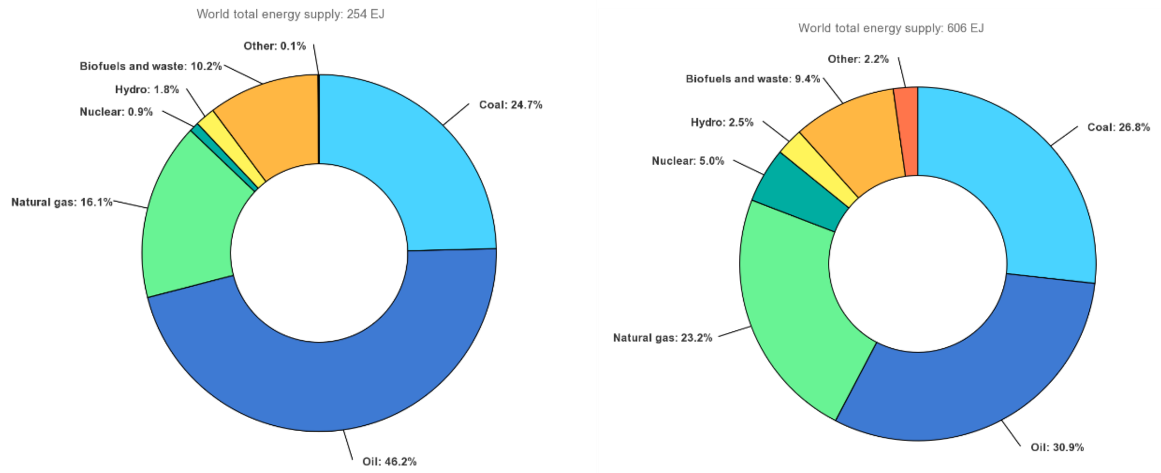

Figure 1.2: Total primary energy supply by fuel, 1971 and 2019. Figure taken from [4] with modifications.

Following BP reports, the increase in primary energy between 2019 and 2021 was almost entirely driven by renewable energy sources, whereas the level of fossil fuel energy consumption was unchanged, with lower oil demand (-8 EJ) offset by higher NG (+5 EJ) and coal (+3 EJ) consumptions[3].
Nevertheless, it is interesting to note that, as the numbers suggest, in the last years the NG demand is growing and it is expected to keep increasing in the coming years (Fig 1.3 shows different hypothesized scenarios for the future NG demand). This is due to lesser environmental impacts associated to NG use, compare to other fossils.
The BP's Energy Outlook 2022 analyzes three main scenarios (Accelerated, Net Zero, and New Momentum) to explore the range of possible pathways for the global energy system to 2050.
The Accelerated and Net Zero scenarios explore how different elements of the energy system might change in order to achieve a substantial reduction in carbon emissions. They are conditioned on the assumption that there is a significant tightening of climate policies leading to a pronounced and sustained fall in CO_2 - equivalent (CO_{2eq}) emissions. On the other hand, the New Momentum scenario is designed to capture the broad trajectory along which the global energy system is currently progressing. It places weight both on the marked increase in global ambition for de-carbonization seen in recent years and the likelihood that those aims and ambitions will be achieved, and on the manner and speed of progress seen over the recent past years [5].
Hence, it can be observed as in this last scenario, the NG is projected to increase in the next years, settling around a constant value reaching the 2050.

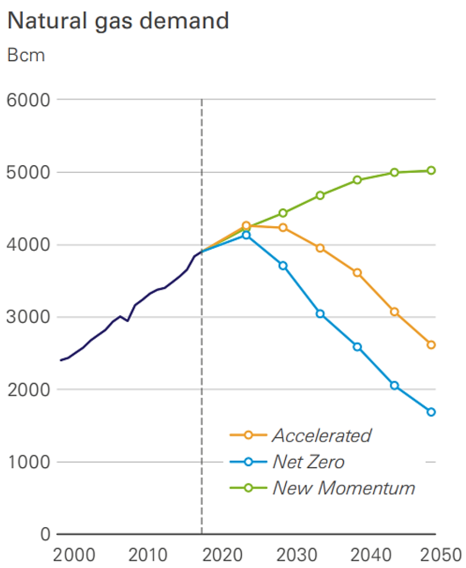

Figure 1.3: NG demand projections, following different scenarios. Figure taken from [5] with modifications.

Therefore, despite NG is a fossil fuel, economies are pushing for its market in the recent years (and also in the following ones). Indeed, despite it is commonly grouped in with other fossil fuels and sources of energy, there are many characteristics that make NG unique. NG is often denominated as *transition fuel* towards a low greenhouse gas (GHG) economy for two main reasons. The first one is that among the fossil fuels, NG results to be the cleanest one: its utilization is associated with about 29% to 44% less CO_2 per unit of energy compared to oil and coal. In addition, combustion of NG emits relatively small amounts of pollutants compared to oil and coal: 20% more and 81% less CO; 79% less and 80% less NO_x; 99,9% less and 99,996% less SO_2; 92% less and 99,7% less particulates, respectively [6].
The second reason is its adaptability: its supply chain could be potentially exploited by other renewable fuels such as syngas, biogas, hydrogen, and bio-methane that are expected to occupy wider percentage in the global energy mix year by year [7].
Following the BP reports, NG is expected to provide a quarter of the global energy demand in 2030 [8]. Considering the increasing importance of NG and its present and future role, this thesis aims to revise the NG supply chain, compare production options focusing on the emerging Floating Liquefied Natural Gas (FLNG) technology, and evaluate different transport options based on the different physical states that are commonly used (compressed NG through pipelines and liquefied NG in methane carriers).

1.3 Comparison between NG transport options: LNG vs pipelines

Nowadays, NG is transported mainly via two options: about 70% is transported by pipelines in the gaseous form and the remaining part as liquefied natural gas (LNG).
The main reason why the gaseous form is the preferred solution is that pipelines proved to be ideally suited to the supply and market conditions of the twentieth century, when large reservoirs of conventional NG have been found in accessible onshore or near shore location.
Nevertheless in the last years, as the demand for NG is steadily growing, attention has been shifted to the so-called *stranded gas fields*. These fields have not been previously exploited both for physical and economic reasons: they may be too remote for being reached by pipelines or, in general, they may require a costly technique for being produced and transported.

In this scenario small-scale LNG producing plants play a central role: they allow the exploitation of these abundant smaller-sized stranded gas reservoirs for which the standard production and transportation method would not be economically or technically feasible.
Briefly, after the production and processing phase (namely the field treatments of the raw reservoir fluids to render them suitable for liquefaction and transportation), NG is liquefied in order to favor the transportation through the reduction of its volume of c. 600 times. Specific ships called *LNG carrier* are used for transporting LNG from the production point to the regasification terminal, where the fossil fuel is reconverted into its gaseous form, to be then fed to NG national transmission systems (Fig. 1.4).
Therefore, a part from the possibility to exploit small reservoirs, another key advantage of LNG is the flexibility of its supply chain that is not constrained by fixed routes as in conventional gas pipeline transmission systems. Moreover, due to more strict specifications (and hence treatments it is subjected to), when LNG is vaporized and used as NG fuel, it generates very low particle emissions and significantly lower carbon emissions than conventional NG itself. Hence, combustion products from LNG tend to contain almost no sulfur oxides and a low level of nitrogen oxides, which makes LNG a cleaner source of energy.

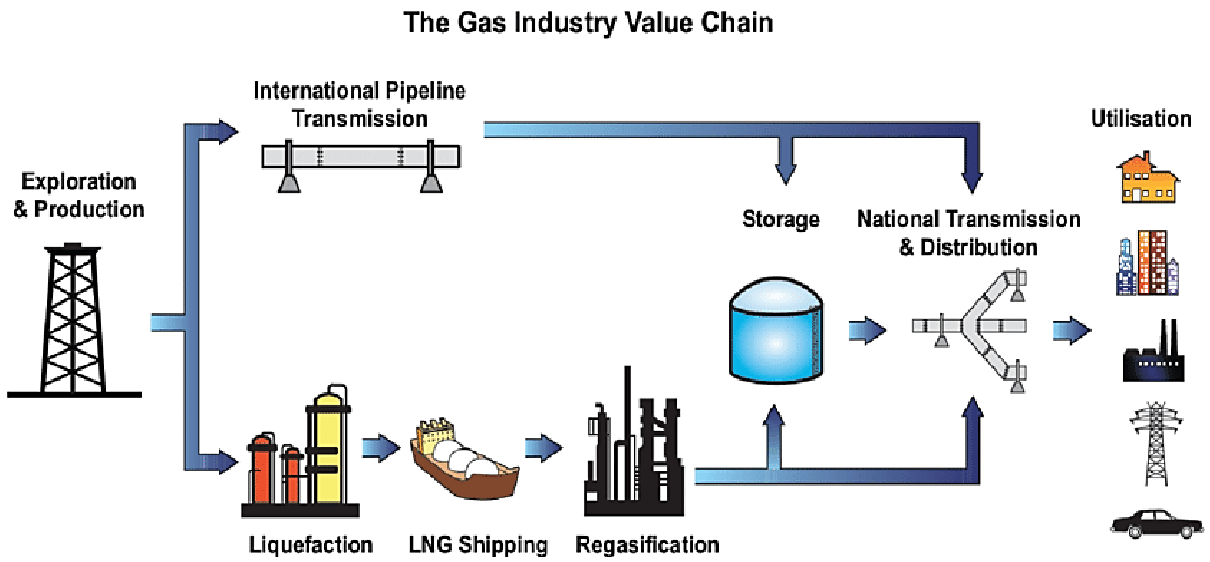

Figure 1.4: The gas industry value chain: two different transport options. Figure taken from [9] with modifications.

Hence, different factors should be considered to determine which transport option can be better suited for a specific application. These factors include: costs, GHG emissions, supply chain robustness, energy consumption and additional environmental impacts.
In general, pipelines are suitable for short-to-medium-length overland transport distances. For these cases, gas pipelines tend to be less costly than LNG, because there is no need for a capital-intensive (and energy intensive) liquefaction plant and regasification terminals. However, when the transport distance increases, there are trade-offs between NG pipelines and LNG to be considered.
Figure 1.5 shows that LNG cost becomes competitive to pipelines for long-distance transport, especially if crossing oceans or long stretches of water bodies is required (the construction of undersea pipelines is cost elevated). Whereas for short distances, gas pipelines are usually more cost-effective. In particular, for offshore stranded gas reservoirs, LNG can be competitive when the offshore pipeline is more than 700 miles while for onshore pipelines, the breakeven point has been suggested around 2200 miles [10].

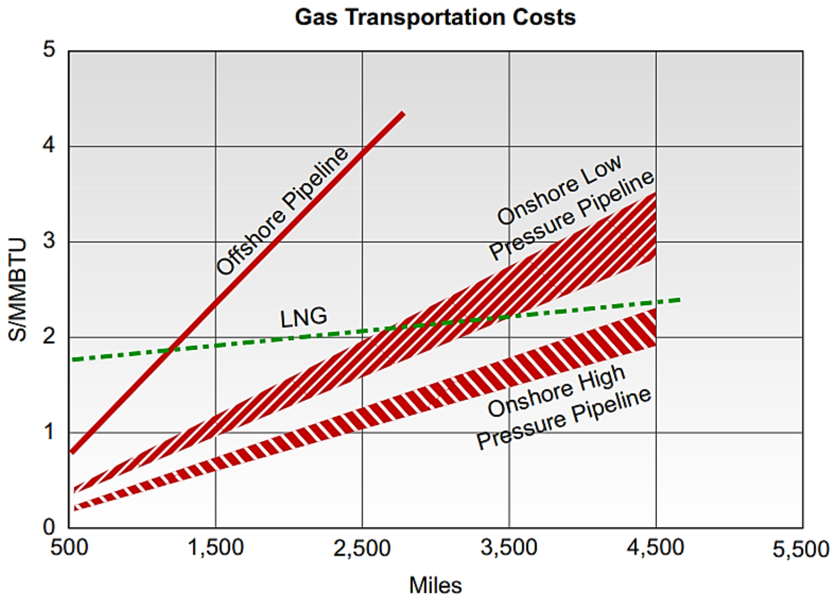

Figure 1.5: NG gas transportation cost following different options. Figure taken from [10] with modifications.

As mentioned above, despite the highlighted advantages in the case of short distances, pipelines present operational drawbacks such as: lack of flexibility in the transport route, dependence of the supply mainly on long-term contracts, supply capacity fixed by the pipeline pressure differential, operation and maintenance of recompression stations, higher risks of fugitive methane, among others.

On the other hand, LNG gives the possibility to easily adjust the supply capacity and destination, making it more adaptable than pipeline gas. As a consequence, it may be a practical solution for improving the security of energy supply of many nations and reducing the geopolitical constraints on global gas supply, which nowadays, is one of the main issues among the world debates.

1.4.1 LNG trade and future perspective

LNG trade, which is a viable option to connect demand and supply for long-distance trade between continents, has experienced impressive growth over the past two decades. Indeed over the last ten years, much of the increased gas production has been traded in the LNG form. This is based on successive waves of investments in NG export and import infrastructures, since LNG trade is playing a central role in increasing emerging markets' access to NG, helping to support economic growth and a shift towards a lower-carbon fuels.

The LNG growth has been driven on the one hand by the United States as main exporters, and on the other one by the increasing gas demand in emerging Asia (China, India and others) as they switch away from coal and, outside of China, continue to industrialize.

Once again, [5] shows three different scenarios for the coming years of LNG trade (Fig. 1.6). In the Accelerated and Net Zero scenarios the use of NG will decrease across much of the world's major LNG demand centers, whereas in the New Momentum scenario LNG imports will continue to expand. In this latter scenario, it is expected to reach over 1000 bcm LNG by 2050 driven by increasing imports to India and other emerging Asian countries, and continuing strong trade to Europe.

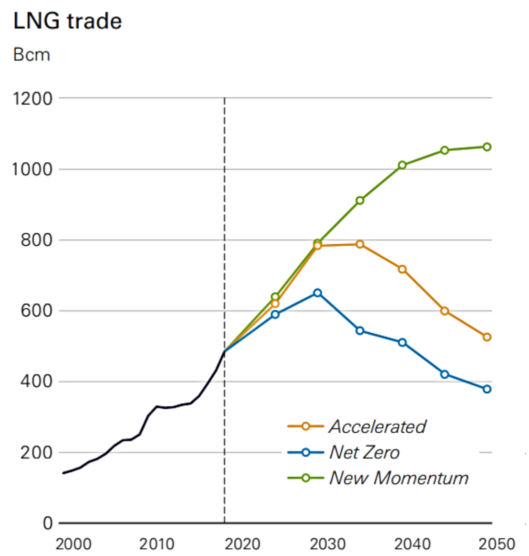

Figure 1.6: LNG trade projections, following different scenarios. Figure taken from [5] with modifications.

LNG markets have grown not only in traded volumes but also in market participants. Nowadays, the major LNG exporters are Australia, Qatar, United States (Fig.1.7), accounting to more than 300 bcm.

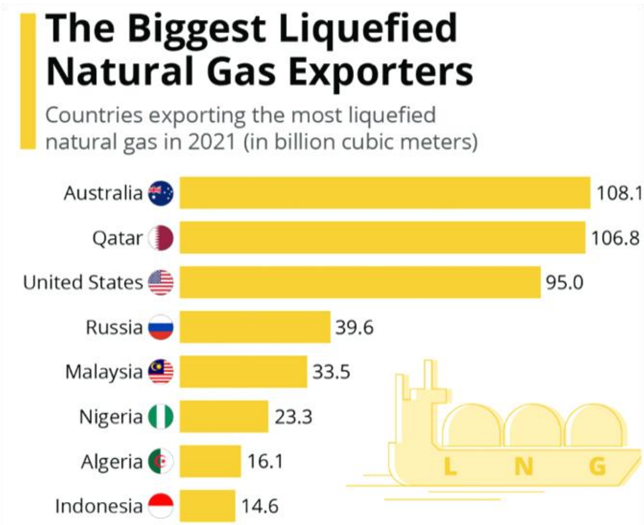

Figure 1.7: Major LNG exporters in 2021. Figure taken from [11] with modifications.

On the other hand, the major importers in 2021 mostly belong to the Asian continent: Fig. 1.8 shows the values representing the billion cubic meters (bcm) exported by country.

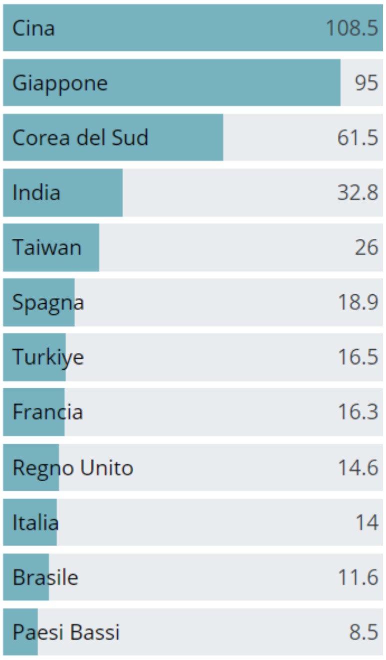

Figure 1.8: Bcm of LNG imported by the major LNG importers in 2021. Figure taken from [12]with modifications.

In 2021, the total LNG exports amount to 516.2 bcm (5.6% higher compared to 2020) which corresponds to about the 12.78% of the total NG production. As a summary, Fig. 1.9 shows the major trade (in NG bcm) movements for the year 2021, both through pipelines and LNG forms.

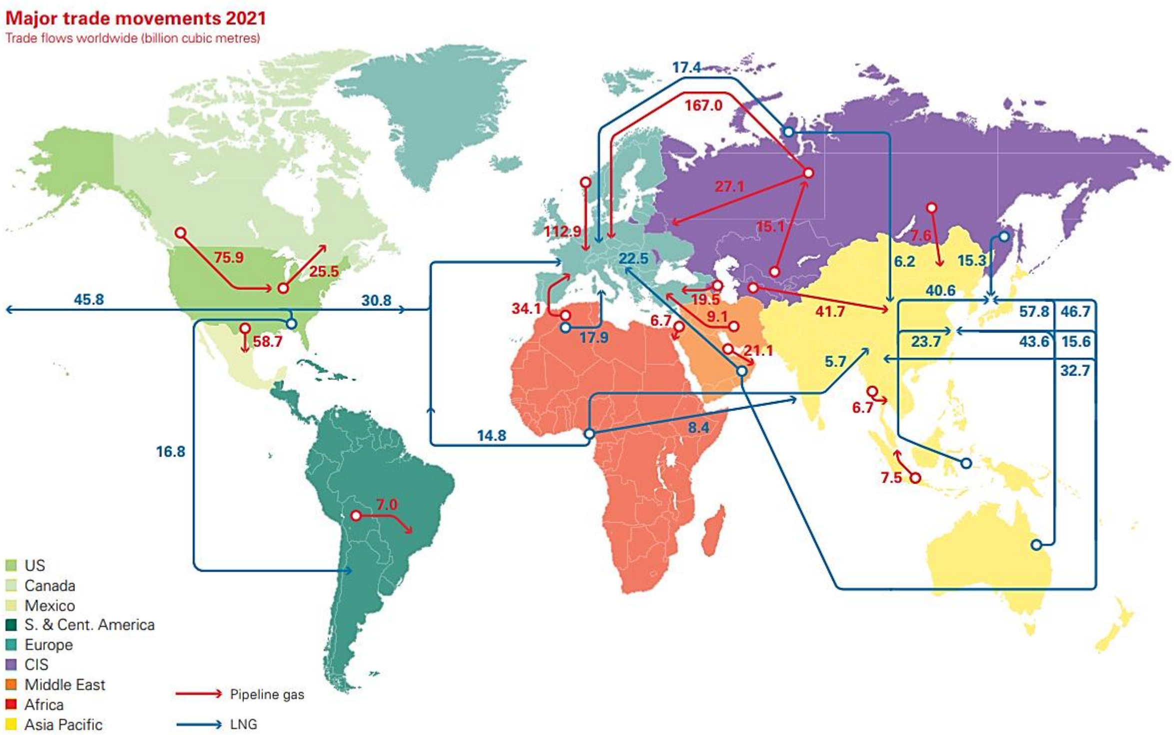

Figure 1.9: Major trade movement in 2021 of NG both by pipelines and LNG. Figure taken from [3] with modifications.

The global LNG market is expected to significantly contribute in the 2022-2026 to Europe's quest to reduce its dependency on Russian gas, by increasing the LNG demand (and use).
In particular, European countries and the UK imported 121 million tonnes of LNG in 2022, recording an increase of 60% compared to 2021, which enabled them to withstand the slump in pipeline gas imports [13]. As a consequence of the emerging role of Europe in the LNG market, the NG demand growth in China and Asia in general, is expected to be curbed as shown in Fig. 1.10.

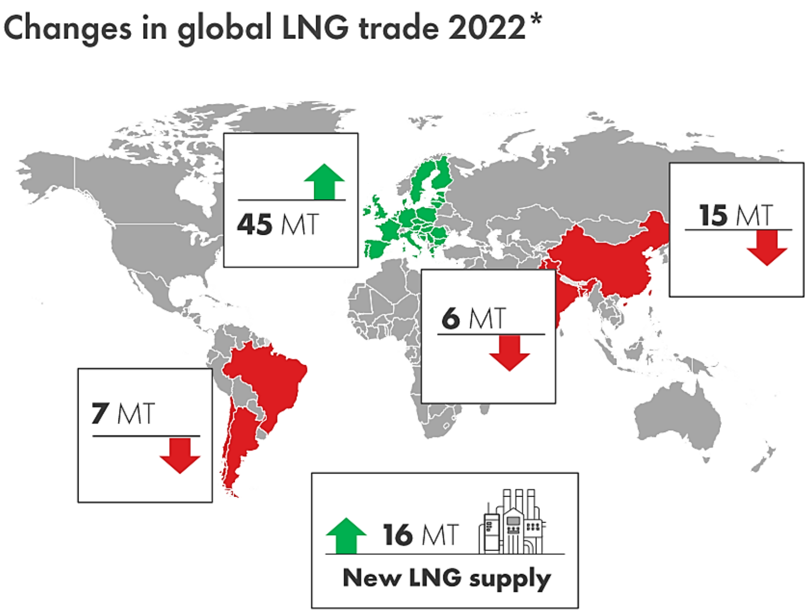

Figure 1.10: Changes in global LNG trade in 2022. Figure taken from [14] with modifications.

Considering the actual LNG market, the ramp-up of new supply projects, especially in the US, is forecast to raise global supply to 460 mtpa, up 19% from 2021 (Fig.1.11).

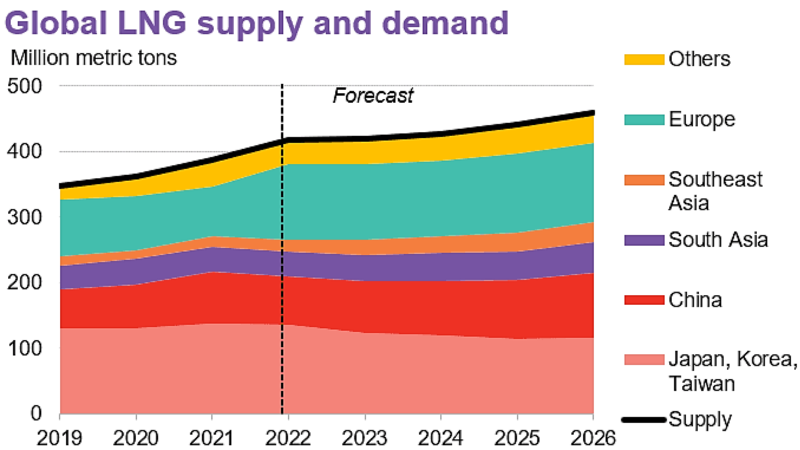

Figure 1.11: Nominal NG liquefaction capacity from 2010 to 2021. Figure taken from [15] with modifications.

1.4.2 LNG production capacity

LNG liquefaction capacity is generally expressed in mtpa (million tonnes per year) of nameplate capacity, namely the intended full-load sustained output of the facility.
In 2021 the global gas liquefaction capacity reached the value of 459.9 million metric tons, showing an increase of about 40% compared to 2010 (Fig. 1.12).

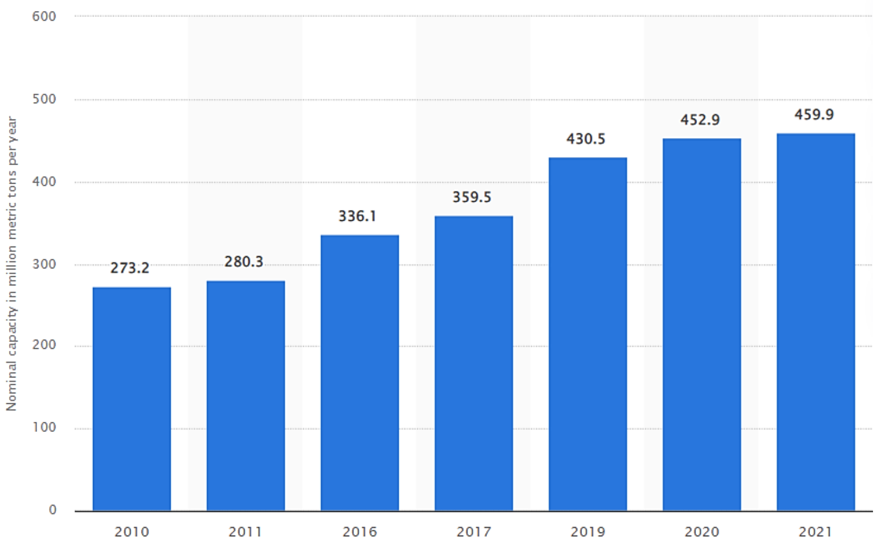

Figure 1.12: Nominal NG liquefaction capacity from 2010 to 2021. Figure taken from [16] with modifications.

Despite these reported numbers, LNG production capacity differes from nominal capacity at any point in time. Many factors can affect LNG export capacity and tracking these fluctuations is a key element to provide an accurate picture of the supply side of global LNG markets.
Operational factors affect the utilisation of a given facility, and they can limit the available capacity relative to the designed one. Ultimately, dealing with these operational factors has a strong influence on the *flow assurance* of production facilities.
The most common factors affecting the capacity of an LNG facility, except planned maintenance operations, are the following:

- Lack of feedstock gas: production from the gas fields feeding the LNG export plant is either in decline or insufficient to meet export needs and domestic consumption. Therefore, gas flow into the LNG plant is below the maximum level. Feed-gas issues were the primary reason for unplanned outages, with a share of approximately 70 to 80%.
- Technical problems: LNG plants are complex sites and they regularly undergo maintenance. Unexpected technical problems can emerge (even during the start-up phases), causing unplanned shutdowns. The lengths of these shutdowns depend on the extent of the problem and scale of the repair works involved. They can even last for years in some cases, especially during early years of operation. Technical problems are responsible for affecting about the 15-20% of the production capacity.
- Security problems: several LNG facilities are located in politically unstable regions, where there is frequent unrest and poor security. This can (occasionally or periodically) result in the evacuation of personnel and partial or total shutdown of the LNG facility. In the worst cases, the export plant can be damaged due to direct attacks or collateral damage.

Figure 1.13 illustrates the total LNG capacity and utilization from 2013 to 2023. It shows the spare capacity both nameplate and available. The first one refers to the capacity which is not utilized because of the oversizing normally done in the design phase. The second one is the actual capacity that it is not exploited. Moreover, the graph shows the liquefaction capacity addition (expressed as bcm) for each year of reference.

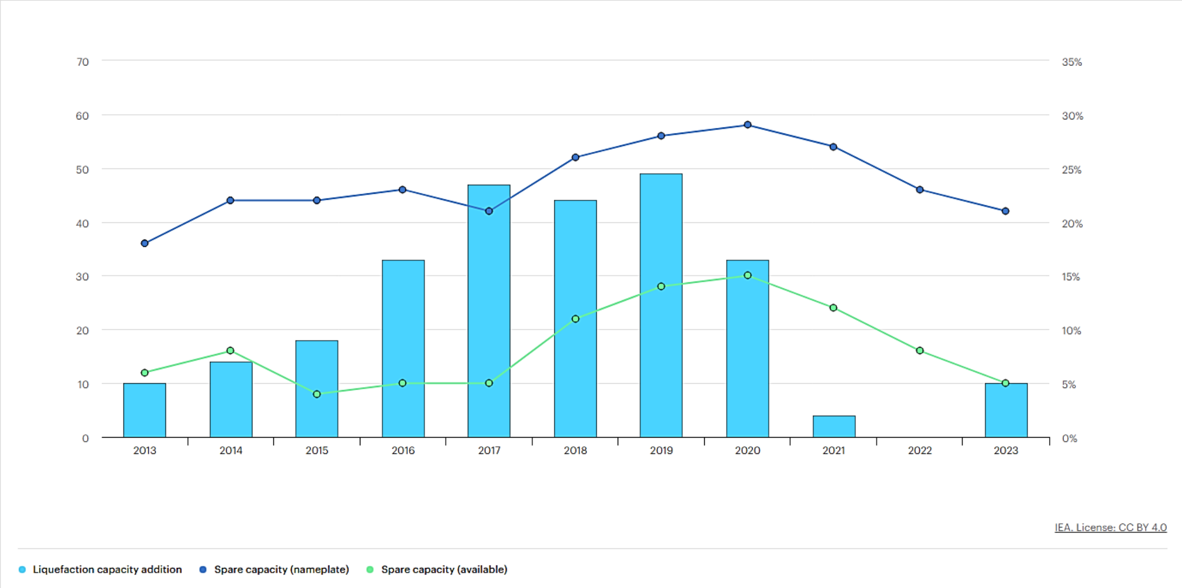

Figure 1.13: LNG capacity and utilization from 2013 to 2023. Figure taken from [17] with modifications.

The graph provides interesting information such as:

- In the last two years despite the liquefaction capacity addition has not significantly increased, both the spare capacities are decreased. It indicates that LNG facilities have been exploited more, leading to a higher LNG production.
- The liquefaction capacity addition, over the last decade (from 2013 to 2020), show the results of the several investments done on LNG industry in the past years.

Non-availability of liquefaction plants reveals that the supply side is limited in its flexibility to provide LNG quantities to the market in times of demand shock. In particular, two factors are important for analyzing the supply side:

- *Load factor*. It is the ratio of the actual output in a given year against the nameplate capacity.
- *Utilization factor*. It is the ratio of the actual output to the potential maximum output (it takes into account both planned and unplanned outages).

Following the reports, in the last decade the former reached an average value of 80%, whereas the second one a value of 90% [18].

1.5 Floating liquefied natural gas (FLNG)

Small-scale LNG facilities, which can be both onshore and offshore, are constructed with the aim of exploiting the remote small gas reservoirs for which it would be not economical and/or technically feasible to build an entire pipeline system. Considering the recent attention towards stranded gas reservoirs, in the last years offshore LNG plants are gaining attention.
Nevertheless, a conventional offshore liquefaction plant is not suitable because: (i) installation of pipelines for transferring NG to onshore LNG facilities is expensive and difficult (complex reservoir fluids, harsh marine conditions and space constrains have to be taken into account), and (ii) it still has environmental and security problems.
As a result, for excavating and monetizing these stranded and offshore reservoirs, floating facilities, denominated Floating Liquefied Natural Gas (FLNG), are considered the best candidates to overcome the mentioned challenges. The FLNG sector deploys marine vessels which result to be the largest in world (Fig. 1.14), reaching a length of almost 500 meters. On these massive structures, the upstream phase of the NG supply chain is carried out comprehending production, processing, liquefaction and storage operations.

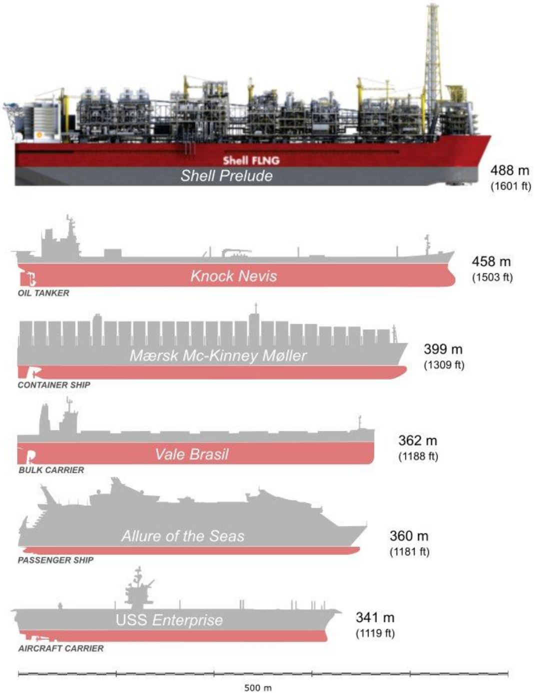

Figure 1.14: LNG tanker sizes. Figure taken from [19] with modifications.

Once that the NG is liquefied and stored on the facility, a second ship called LNG carrier is used for the transportation of LNG from the floating plant to the regasification terminal, where the liquefied product is converted into a gaseous one for being transmitted through the distribution network (pipelines systems).

The development of the FLNG concept started in the 1950s [20]and nowadays, the major FLNG projects include: Shell Prelude FNLG (2017), Petronas FLNG 1 (2016), Petronas FLNG 2 (2020) and Coral Sul FLNG (2022).

Figures below (Fig.1.15-1.18) show the mentioned facilities and the respective location where they are currently operating.

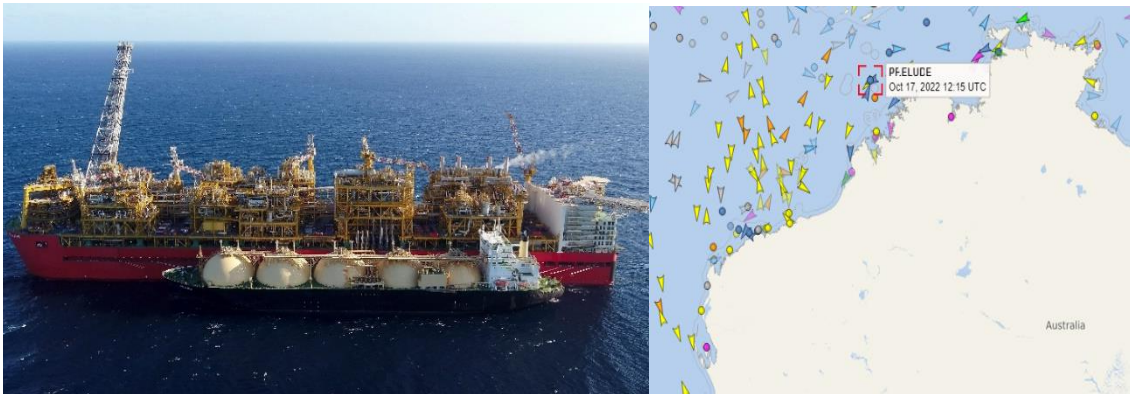

Figure 1.15: Prelude FLNG (Shell) and operational location (Australia) [21].

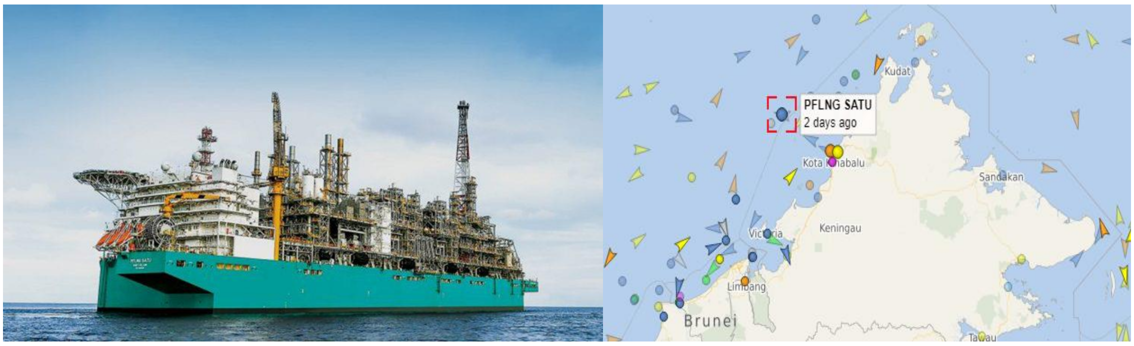

Figure 1.16: Petronas FLNG 1 (SATU) and operational location (Malaysia)[21].

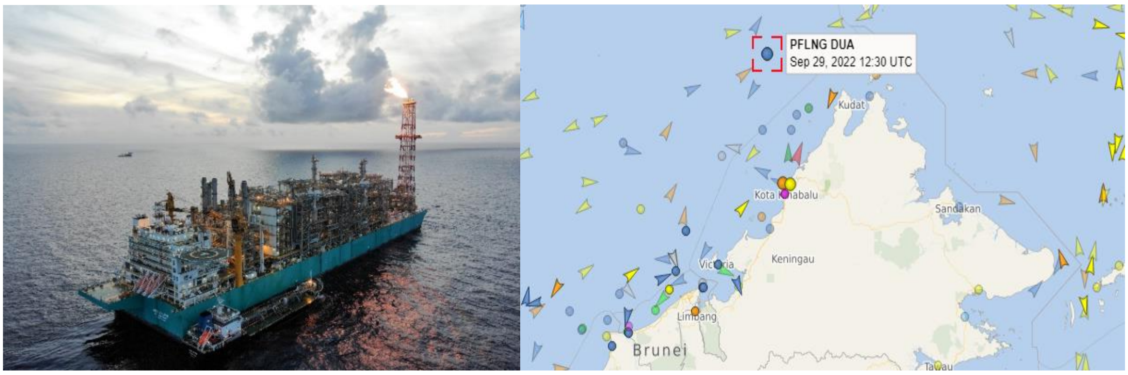

Figure 1.17: Petronas FLNG 2 (DUA) and operational location (Malaysia) [21].

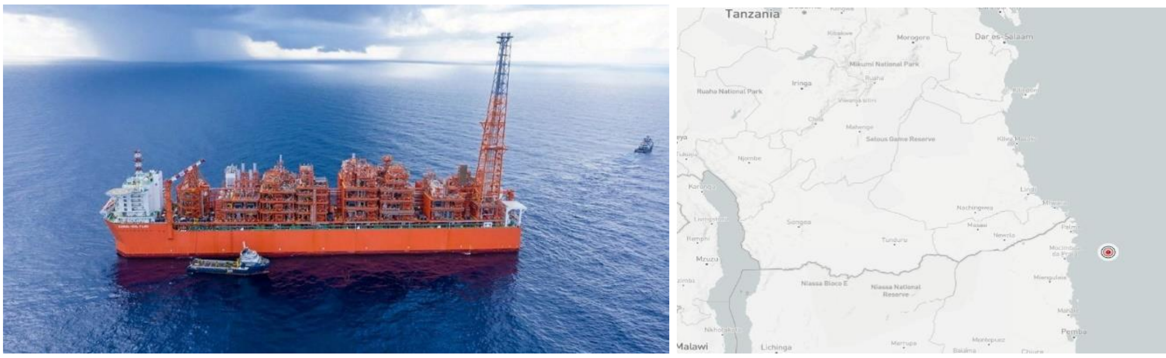

Figure 1.18: Coral Sul FLNG (Eni) and operational location (Mozambique) [22].

The main characteristics of the mentioned facilities are summarized in Table 1.1.

Table 1.1. Summary of the main FLNG facilities.

	Prelude	Petronas 1	Petronas 2	Coral Sul
Length [m]	488	365	393	438
Weight [ton]	260.000	125.000	134.000	220.000
Capacity [mtpa of LNG]	3,6	1,2	1,5	3,4
Year of construction	2012	2013	2015	2016
Year of production	2018	2017	2021	2022

In particular, the present thesis will be focusing on the Coral Sul FLNG project.

As shown in Table 1.1, this infrastructure is characterized by a capacity of 3,4 mtpa of LNG which is the equivalent of about 5 billion cubic meters of natural gas. Considering that in 2021 the NG consumption in Italy and Switzerland reached 76,1 and 3,6 billion cubic meters respectively, Coral could be potentially able to cover about 6,57% and 139% of the NG demand in these countries.

2. Natural gas supply chain: theoretical background

Natural gas is a mixture of short-chain hydrocarbons such as methane (which covers the largest percentage), ethane, propane, butane and even heavier compounds (Fig. 2.1).

Name	Molecular Formula	Melting Point (°C)	Boiling Point (°C)	Density at 20°C (g/mL)
Methane	CH_4	−183	−162	(Gas)
Ethane	C_2H_6	−172	−89	(Gas)
Propane	C_3H_8	−188	−42	(Gas)
Butane	C_4H_{10}	−138	0	(Gas)
Pentane	C_5H_{12}	−130	36	0.626
Hexane	C_6H_{14}	−95	69	0.659
Heptane	C_7H_{16}	−91	98	0.684
Octane	C_8H_{18}	−57	126	0.703
Decane	$C_{10}H_{22}$	−30	174	0.730
Dodecane	$C_{12}H_{26}$	−10	216	0.749
Tetradecane	$C_{14}H_{30}$	6	254	0.763
Hexadecane	$C_{16}H_{34}$	18	280	0.775
Octadecane	$C_{18}H_{38}$	28	316	(Solid)
Eicosane	$C_{20}H_{42}$	37	343	(Solid)

Figure 2.1: Mixture of hydrocarbons in a typical NG. Figure taken from [23] with modifications.

Considering its composition, NG can be exploited both as fuel and as a raw material (feedstock) to produce chemicals, fertilizers and hydrogen. Different applications are possible also in other sectors, as an example Fig. 2.2 shows the U.S. NG consumption by sector in 2022.

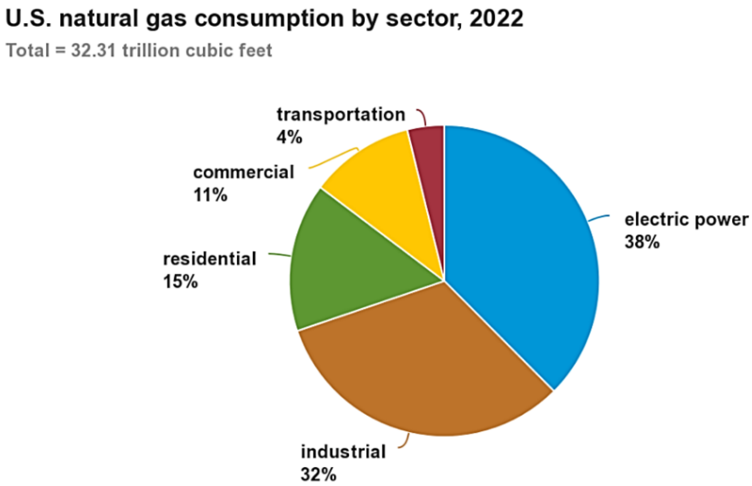

Figure 2.2: U.S. NG consumption by sector, 2022. Figure taken from [24] with modifications.

Apart from hydrocarbons, in a typical NG reservoir, other substances are present in a smaller amount, such as water, nitrogen, carbon dioxide and sulfur compounds.

The exact composition of NG varies by geographic region, age of the deposit, depth and many other factors. However, a typical average composition before any kind of treatment is shown in Tab. 2.1.

Table 2.1. Compositions range of a NG. Table taken from [25] with modifications.

Compound	Formula	% in NG
Methane	CH_4	40-97%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	0-20%
Butane	C_4H_{10}	0-20%
Carbon dioxide	CO_2	0-60%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-25%
Hydrogen sulphide	H_2S	0-40%
Rare gases	A, He, Ne, Xe	Traces

Nevertheless, a part from the compounds shown in Tab. 2.1, other substances may be present in the raw NG composition. These substances categorizes NG as follow:

- *Sour*, *sweet* or *acid*. It is a classification based on the amount of acid gases. *Sweet* NG contains trace amounts of H_2S (less than 4 ppm), whereas *sour* NG contains large amounts. As a consequence, the former, being less acidic and non-corrosive, requires a non-intensive refining, and results to be easily handled and transported. On the contrary, the latter, being corrosive, may damage piping due to sulfide stress cracking phenomena, hence requires more refining. A part from H_2S, other acid gases (e.g., CO_2, HCl, HF, SO_x, and NO_x, among others) may be found in raw NG in varying concentration. These gases, can damage materials in contact with them, and can be harmful for human health. Raw NG is denominated *acid*, when the acid gases content is higher than the 20%.
- *Wet* or *dry*. *Wet* NG contains a consistent portion (higher than 95%) of hydrocarbons heavier than methane (e.g., ethane, propane and butane, among others). These compounds are condensable when brought to atmospheric pressure, and are frequently separated as *natural gas liquids* (NGLs). On the contrary, *dry* NG is mainly composed of methane and only negligible amounts of heavier hydrocarbons may be revealed.

There are two primary sources of raw NG: *associated* gas reserves and *non-associated* gas reserves. In the former, NG is produced as byproduct of the production of crude oil, and normally it is either reinjected, flared or vented. This gas is always *wet*, since it is saturated by the more volatile compounds of the oil which it is in contact with.

On the contrary, *non-associated gas* reserves are exploited primarily to produce NG. There may or may not be condensate production together with the gas.

Nowadays, following [3]the top producing countries of NG in the world are the United States (28,1%) followed by Russia (17,4%), Iran (6,4%), China (5,2%), Qatar (4,4%), and Canada (4,3%).

2.1 NG quality specifications

Natural gas to be transported has to meet several quality specifications. Gas companies generally define gas quality as the chemical composition of the gas, with all its different species such as various hydrocarbons, inert gases (nitrogen, carbon dioxide) as well as undesirable

species like sulphur compounds, water and mercury. Indeed, for some major gas users, such as the chemical industry which uses NG as a feedstock, the process has to be properly tuned to a given gas composition. Moreover, adjustments might be required to meet the typical combustion quality characteristics such as the Wobbe Index, the calorific value and methane number, ensuring a clean, safe, energy efficient and reproducible performance.
Nevertheless, a global harmonization for NG quality specifications does not exist. As a consequence, each country has its own standards that have to be met from the suppliers for avoiding the risk to have their gas rejected by the transmission system operators (Table 2.2a-2b).
As mentioned above, NG can be supplied to a country via two main options: it can be imported from neighboring countries at interconnection points through pipelines or it can be imported as LNG through LNG terminals. In this regard, meeting the standards is also important for the transportation phase in order to assure a safe, clean and not harsh environment that could lead to a frequent maintenance of the transportation system itself.
In conclusion, the gas stream must meet a series of specific values for each parameter such as:

- *Wobbe Index (WI)* [kWh/Nm^3]: is the main indicator of the interchangeability of fuel gases. WI is used to compare the combustion energy output with different composition of fuel gases. Meaning that if two fuels have identical WIs at a given pressure and valve setting, then the energy output will be the same one. Therefore, WI is a critical factor in minimizing the impact of fluctuations in fuel gas supply. It is defined as the gross calorific value over the squared root of the gas mixture relative density.
- *Gross Calorific Value* [kWh/Nm^3]: is the amount of heat evolved by the complete combustion of a unit certain volume of gas with air.
- *Relative Density*: is the density of gas in relation to the density of air, when both are at the same reference conditions.
- *Water* and *Hydrocarbon Dew Point* [°C]: Hydrocarbon Dew Point is the temperature (at a given pressure) at which the hydrocarbon components of any hydrocarbon-rich gas mixture, such as NG, will start to condense out of the gaseous phase. Hydrocarbon Dew Point is a function of the gas composition as well as the pressure. Instead, the Water Dew Point is the temperature (at a given pressure) at which water vapor present in a gas mixture will condense from the gas.
- *Hydrogen Sulphide (H_2S)* and *Mercaptan Sulphur* [mg/m^3]: are hydrocarbon molecules wich contain sulfur. When present in sufficient concentrations, these compounds can lead to serious problems such as increased corrosion rates or can pose higher risk for the human health. Odorants added for safety reasons often also contain sulfur which may explain why sulfur content can be very different if a country has odorized its gas on the transmission network.

Table 2.2a: NG quality specifications for different countries [26].

Country	Italy	France	Spain	Germany	Switzerland	Belgium
Wobbe Index [kWh/Nm^3]	13,86÷15,33	14,13÷16,56	14,1÷16,89	13,08÷15,82	14,70÷14,82	12,2÷13,02
Gross Calorific Value [kWh/Nm^3]	10,24÷13,27	11,28÷13,5	10,79÷13,95	8,86÷13,81	10,17÷10,37	9,53÷10,74

Relative Density [No Unit]	0,555÷0,8	0,555÷0,7	0,555÷0,7	0,55÷0,75	0,578÷0,610	0,555÷0,7
Water Dew Point [°C]	-5	-5	2	Ground temperature at a given pipeline pressure	NA	-58÷-15,5
Hydrocarbon Dew Point [°C]	0	-2	5	NA	NA	-15÷-6
Total Sulphur [mg/m^3]	150	150	50	30	7	30
Hydrogen Sulphide [mg/m^3]	6,6	5	15	5	NA	5
Mercaptan Sulphure [mg/m^3]	15,5	6	17	6	NA	6
Oxygen [%mol]	0,6	0,01	0,01	NA	NA	0,00001
Carbon Dioxide [%mol]	3	2,5	2,5	NA	NA	2,5

Table 2.2b: LNG quality specifications for different countries [26].

Country	Italy	France	Belgium
Wobbe Index [kWh/Nm^3]	13,14÷15,53	13,40÷15,56	14,17÷15,56
Gross Calorific Value [kWh/Nm^3]	11,18÷12,65	10,27÷12,75	10,83÷12,43
LNG Density [kg/m^3]	430÷470	NA	425÷480
Water Dew Point [°C]	≤-5	NA	-58
Hydrocarbon Dew Point [°C}	≤0	NA	-20
Total Sulphur [mg/m^3]	≤21	21	22,4
Hydrogen Sulphide [mg/m^3]	≤5,27	5	5
Mercaptan Sulphure [mg/m^3]	≤6,32	NA	6
Oxygen [%mol]	≤0,6	0,01	0,001
Carbon Dioxide [%mol]	≤2,5	NA	0,01
Mercury [ng/Nm^3]	10,55	50	50

It is interesting to note (from Table 2.2a-2b) that the values required for LNG are stricter compared to the NG ones. Indeed, for LNG a lower level of impurities at the end of the processing phase, is required due to the intensive liquefaction process. For example, nitrogen removal is mandatory since its boiling temperature at atmospheric pressure is -195,8 °C which is considerably lower compared to the one of methane (-162 °C). Moreover, other specifications are needed for the LNG such as the mercury content. Indeed, mercury at cryogenic temperatures solidifies causing corrosion or erosion problems on pipelines and equipment.

2.2 The conventional upstream stage

The NG supply chain can be seen as consisting of three main phases:

- *Upstream*: production and processing phase.
- *Midstream*: transport phase.
- *Downstream*: storage and distribution phase.

As mentioned above, NG for being sold and transported via pipelines must meet several quality specifications that may include parameters such as calorific value, composition, contaminants, water content, and hydrocarbons dew point. These parameters are standardized and may vary widely depending on the Country of reference, pipeline system, climatological conditions and end-uses. In this context, performing an effective upstream phase is mandatory.

The upstream phase consists of the extraction phase (the so-called production phase) and the processing one, which includes a series of treatments. When NG is extracted from the well (from associated or non-associated reservoirs), requires mandatory processing the mixture in the field. The reason of that is due to the fact that the extracted mixture of reservoirs fluids (crude oil, natural gas, salt, water, solid debris) is very difficult to handle and transport. Indeed, it results to be both unsafe and uneconomical to ship or transport the mixture to refineries and plants for processing.

The field processing has three main objectives:

- Producing a transportable stream. For the pipeline transportation some components such as water, hydrogen sulfide, condensate, have to be managed.
- Producing a salable stream meeting specifications.
- Maximizing liquid production. It is possible for example by recovering the condensate and re-injecting the gas to the reservoir.

In general, production is stopped when the water fraction reaches high values and the hydrocarbon streams are not sufficient for covering the production costs themselves. The ratio produced water over produced oil has to be equal or lower than 3.

A schematic representation of the apparatus conventionally employed for the extraction of a reservoir is shown in Figure 2.3.

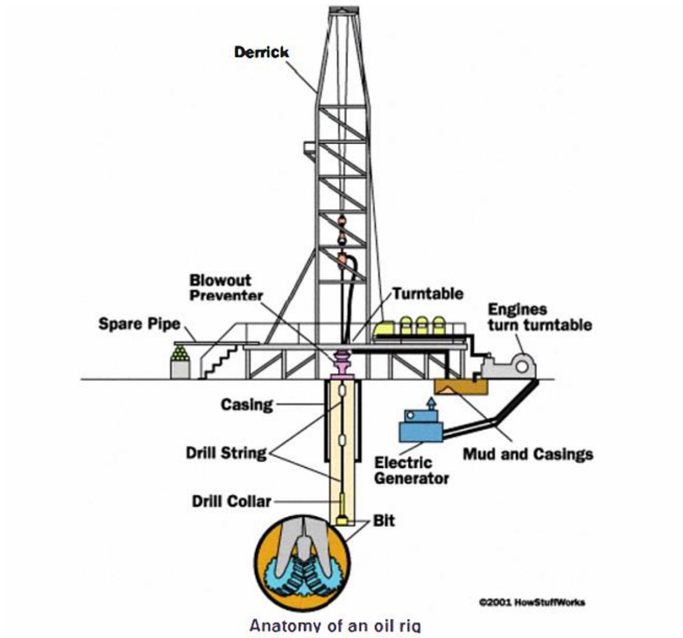

Figure 2.3: Schematic of a production apparatus. Figure taken from [27] with modifications.

Nevertheless, as mentioned, production can be both onshore and offshore and it can include not only fixed platforms but also floating ones (Fig. 2.4)

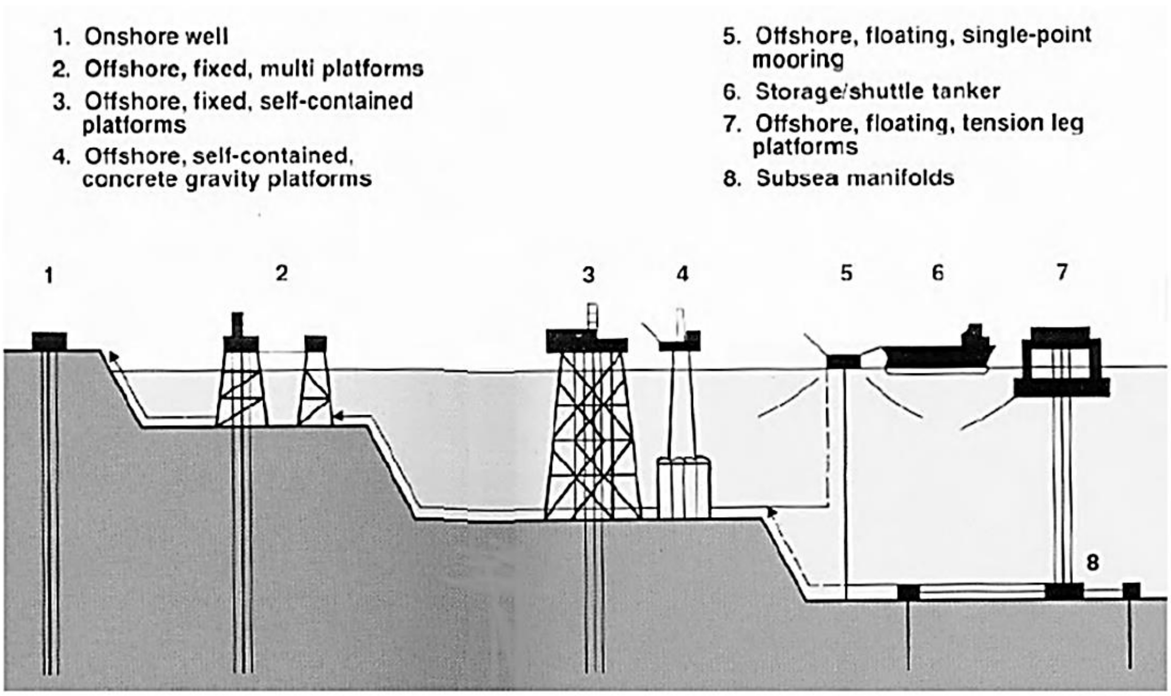

Figure 2.4: Schematic of a different production apparatus. Figure taken from [28] with modifications.

Considering the intensive extraction required by the global demand, different technologies have been developed over the years in order to improve the recovery of each reservoir.
These techniques include:

- *Primary recovery*. The well produces a fluid by using the natural potential energy of the reservoir. Extraction can be facilitated by gas lift (injection of gases for reducing density and viscosity of the reservoir) and pumping systems.

- *Improved oil recovery*. Injection of a fluid (water or the gas produced by the extraction itself) in order to maintain a sufficient reservoir pressure for the production.
- *Enhanced oil recovery*. Injection of thermal energy or gases soluble in water and oil or chemicals that allow a higher production.

2.2.1 Phase separation

The produced well fluids are mainly composed of oil, gas, water and solid sediments. Hence, after the extraction, the mixture is sent to the processing facility (using the so-called gathering systems), where the first step consists of phase separations (solid, liquid and gas). For this purpose, two- or three-phase separators are used.
Depending on the case, this equipment can be both horizontal (Fig. 2.5) and vertical (Fig. 2.6) and each option has different advantages and disadvantages. In general, the axial orientation mostly depends on the gas-to-oil (GOR) value (ratio between the volume of gas produced over the volume of oil produced). When GOR reaches high values (about 5000) a vertical configuration is favored. Nevertheless, other criteria are applied for choosing the best option and they are summarized in Table 2.3.

Table 2.3: Performances of vertical (V) or horizontal (H) three-phase separators.

	Type	**Advantage**
Separation of phases	H	The liquid drops or gas bubbles do not have to settle or rise through a countercurrent flow
Separation of solids	V	Solids are more easily removed from the bottom of a vertical vessel and are concentrated in a small section
Reduction of foam	H	A higher surface area is provided for bubbles to escape and open in the gas phase
Surge control	V	A first change of liquid level is easily monitored

Therefore, in horizontal configurations, the phase separation is more efficient than the vertical one (where the efficiency decreases due to the countercurrent flow of the gas with respect to the feed the mixture enters the structure axially). On the other hand, the vertical separator assures a more effective separation of the solid cut. Moreover, the selection depends also on the space availability: the horizontal one requires more space. On the other hand, the vertical separator is difficult to reach and to service top-mounted instruments and safety devices.
Although the separator can have different structural configurations, the working principle is always the same: it takes advantage of gravity for obtaining separated streams of oil, gas, water. In the horizontal one (Fig. 2.5) the fluid enters horizontally and hits an inlet diverter that provides a gross separation of the liquid and gaseous phase. The liquid collection section of the vessel must provide sufficient time for oil and emulsion to form a layer above the free water. A weir maintains the oil level while an interface controller maintains the water one. In general, different controllers are present into this system to properly maintain both the oil and the water level. The gas phase exits, often through a mist extractor which is placed in the upper part of the vessel in order to separate the liquid droplets from the gas stream before it leaves the unit. A pressure control valve is present with the function of maintaining a constant pressure in the vessel.

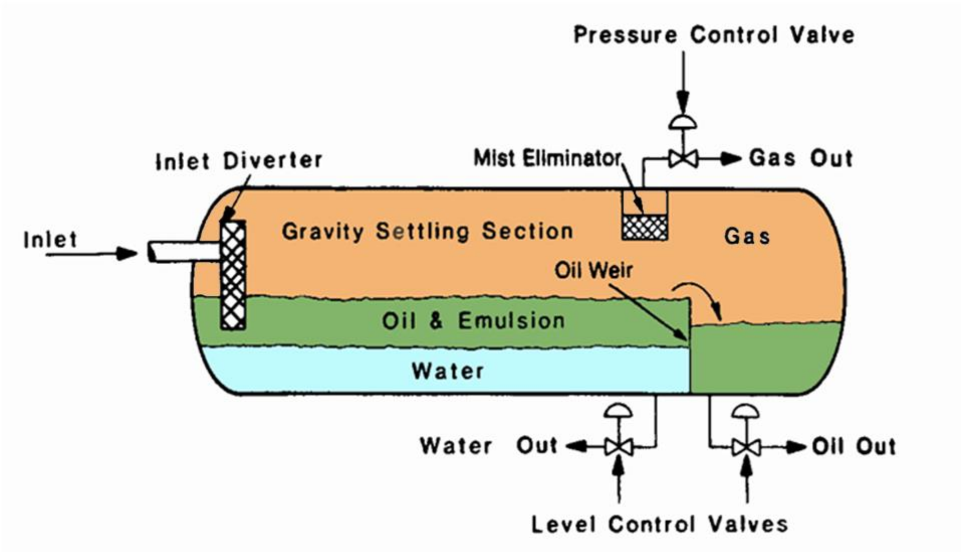

Figure 2.5: Typical horizontal three-phase separator with internals. Figure taken from [29] with modifications.

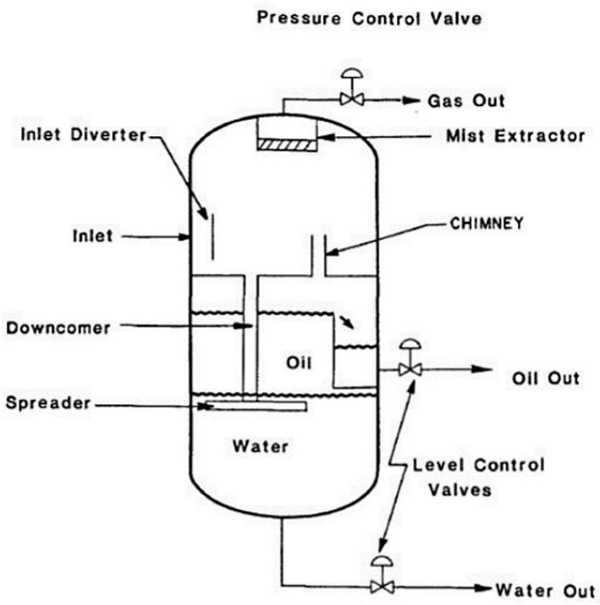

Figure 2.6: Typical vertical three-phase separator with internals. Figure taken from [30] with modifications.

These kind of equipment may be also used as test separators for periodic or continuous quality flow measurements which could be useful for several reasons such as:

- Determining how the well is performing and how much oil, water, and gas are produced.
- Fine-tuning recovery operation to maximize retrieval of hydrocarbons.
- Managing the decline curve of the wells.

2.2.2 Dehydration

After the separation of the main components of the raw mixture coming from the well, the processing phase of NG continues and each obtained stream undergoes a dedicated chain of processing steps (Fig. 2.7).

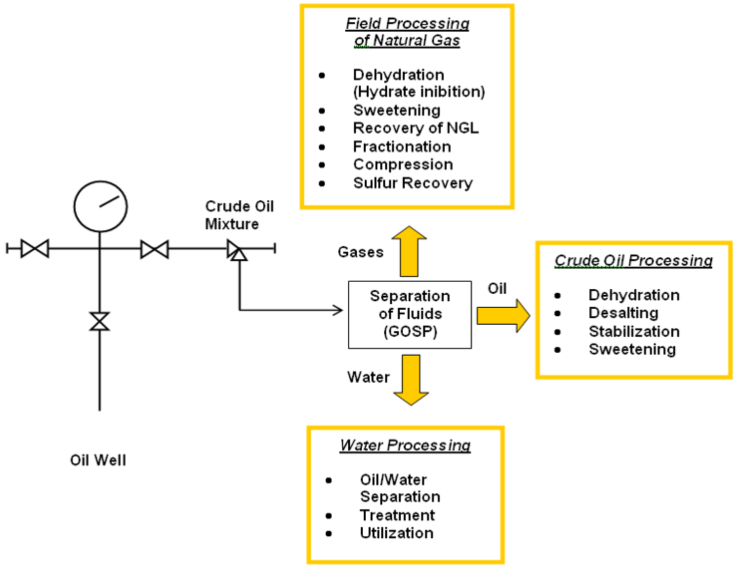

Figure 2.7: Summary of processing phase for NG. Figure taken from [31] with modifications.

The main impurities in NG are water, acid compounds (sulfur compounds and carbon dioxide) and heavier hydrocarbons, which are treated by the dehydration process, the sweetening process and the condensate recovery, respectively.
The first operation to be performed is the dehydration one. As mentioned, the production of crude oil and NG is usually associated with the production of water which needs to be removed in order to:

- Prevent hydrate formation. The presence of water along the production line may create the conditions for hydrate formation which can cause problems to pipelines and equipment due to their solid phase.
- Avoid corrosion problems. The components found in NG, when liquid water is present, may be corrosive.
- Meet the downstream processing requirements. The presence of water may cause side reactions, foaming and catalyst deactivation. Moreover, the more the content of water the lower the calorific value of the final product.
- Meet sales contract specifications. Purchasers typically require that the final gaseous product meets certain specifications for the maximum water content.
- Prevent phenomena such as freezing in cryogenic plants, decreasing in the heating value of the gas, erosion.

Regarding hydrates, they are solid crystalline compounds formed when water and light hydrocarbons (C1-C5) are present at high pressure and relatively low temperature (Fig. 2.8): the hydrocarbon molecules are trapped into a solid matrix of iced water.

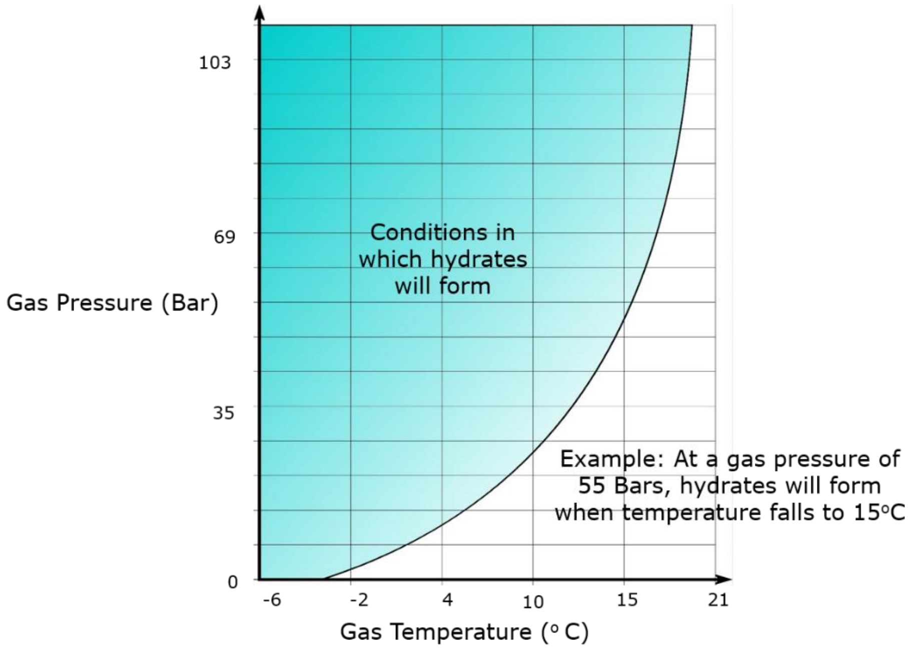

Figure 2.8: Conditions for hydrates formation in NG. Figure taken from [32] with modifications.

These conditions may be easily reached into the pipelines, for this reason the hydrates removal is necessary since the main consequence of their presence is the plugging of the pipelines themselves and the blockage of valves. Moreover, even though the formation occurs at low temperatures, hydrates result to be (meta)stable also at ambient ones.
There are several methods for avoiding hydrates formation:

- Reducing the water content of the system (dehydration).
- Removing forming and promoting species (sweetening).
- Going out of the formation region (Fig. 2.8).
- Adding hydrate preventing chemicals (inhibitors such as methanol, ethylene glycol).

The dehydration process is usually performed following one of the following strategies:

- Absorption by a liquid desiccant (glycols).
- Adsorption by a solid desiccant (alumina, silica gel, molecular sieves).
- Performing a low temperature process.

Absorption processes are characterized by a counter current contact of a liquid and a gas phase (NG). The scope is the removal from the gas phase of a part of its components that, consequently, are absorbed by the liquid phase itself. A reverse process (the so-called *desorption*) can be performed on the saturated liquid phase, by the addition of heat, in order to re-use it into the process.
In this particular case, the absorption process exploits a liquid desiccant (in most of the applications glycols are used, such as: ethylene glycol, diethylene glycol, triethylene glycol, tetraethlylene glycol) due to its affinity to water. After this operation, the greatest content of water vapor is removed from the initially fed gas stream.
The absorption process is performed into columns where glycol and NG are normally fed with counter current flows (liquid from the top and gas from the bottom). Three types of columns are commonly used:

- Tray columns.
- Columns with structured packing.
- Columns with random packing.

When a large volume of gas needs to be managed, tray columns result to be a more suitable solution. Usually, the number of plates can vary from 4 to 12: the higher the number the higher the moisture content removed.
In the most common configuration, on each tray a series of bubble caps are placed in order to favor the exchange between the two phases (Fig. 2.9).

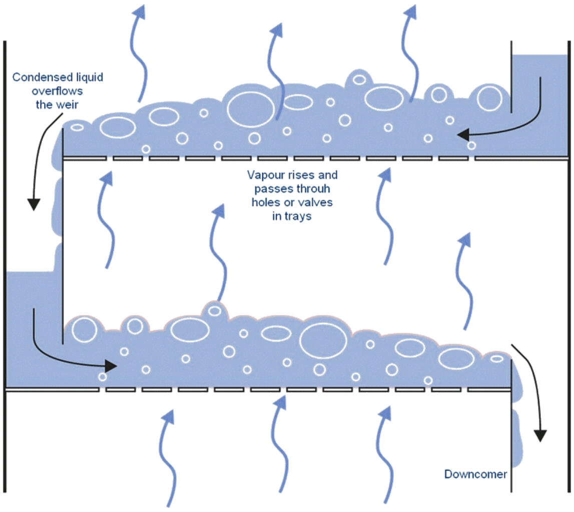

Figure 2.9: Schematic of internal configuration of a tray column. Figure taken from [33] with modifications.

On the other hand packed columns, both structured and random, are smaller capacity units. They result to be cheaper compared to the previous case but they may face non-homogenous distributions of the liquid phase, since channeling phenomena can take place (for this, liquid redistributors are typically installed along the columns). The packing material can be of different shapes and materials and its scope is ensuring a better contact between the phases (Fig. 2.10).

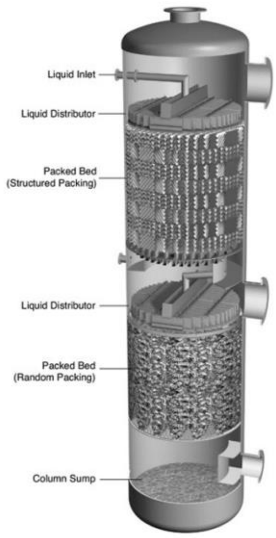

Figure 2.10: Typical packed tower. Figure taken from [34] with modifications.

A typical glycol dehydration unit, including the equipment needed for the regeneration phase, is represented in Figure 2.11.

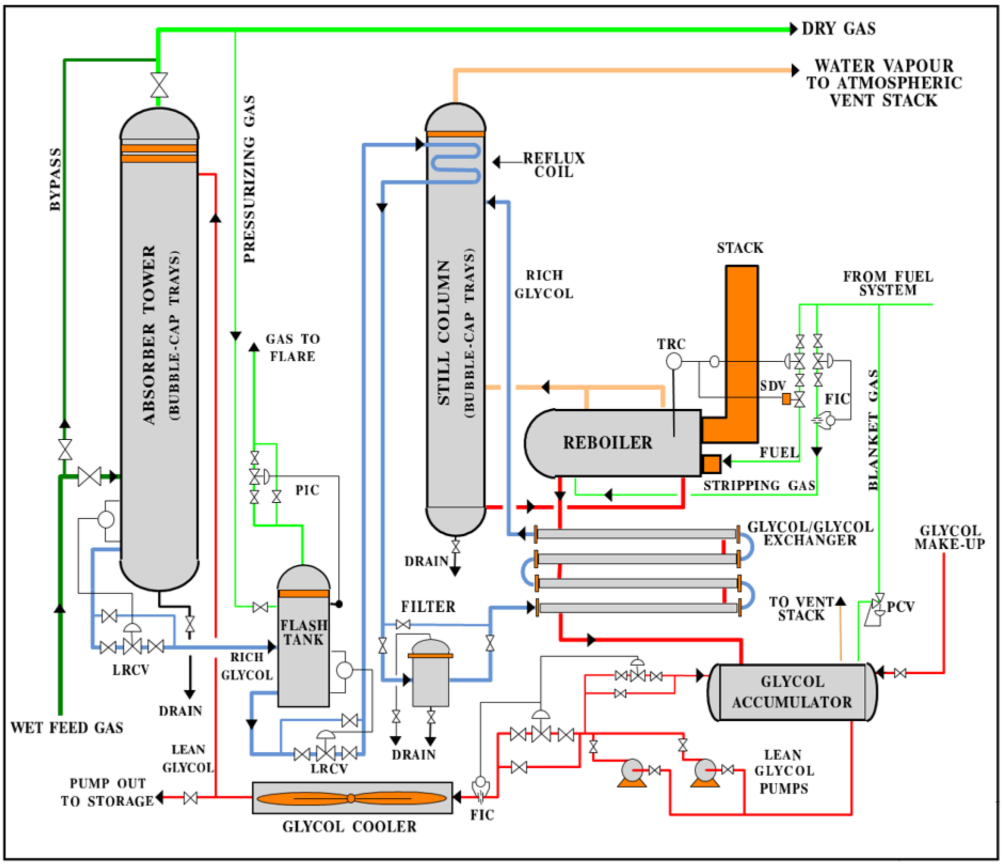

Figure 2.11: Typical glycol dehydration unit. Figure taken from [35] with modifications.

Adsorption differs from absorption due to the presence of a solid phase, instead of a liquid one, for the removal of the water vapor. This is a surface phenomenon where gas or part of its components diffuse through the pores of the solid. Adsorption can be both physical and chemical. In the first case, weak bindings (Van Der Waals interaction) between the solid and the gas are formed and they can be easily broken by increasing the temperature. Differently from the physical type, the chemical one is an irreversible process where reactions occur between the two phases and the solid cannot be recovered due to the strong formed chemical bonds. In both cases the desiccant is a granular dehydrating medium with an extremely large effective surface area per unit weight because of a multitude of a microscopic pores and capillarity openings (a typical solid desiccant can have an interfacial area as high as 4 millions square feet per pound).
Generally, the physical type is used and the most common solid adsorbents (place into packed columns like the absorption configuration) are:

- *Silica gel* (SiO_2), when a high concentration of water vapor (higher than 1 % M) is present in the feed and low levels of water in the dehydrated gas are not needed.
- *Activated alumina* (Al_2O_3), used for moderate levels of water in the feed and when low levels of water in the product are not required.
- *Molecular sieves* (such as zeolite), for achieving very low water concentrations. It results to be very suitable for cryogenic processes such us the ones needed for LNG (Fig. 2.12).

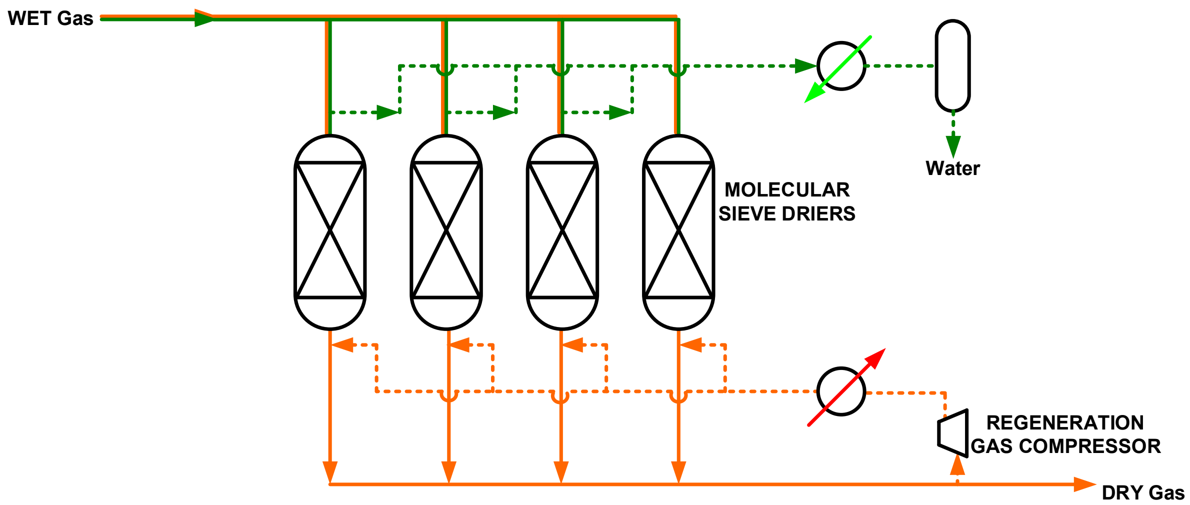

Figure 2.12: Schematic of a molecular sieve driers adsorption unit. Figure taken from [36] with modifications.

As initially mentioned, a third method for removing water vapor from a NG stream is lowering the temperature below the water dew point in order to condense out the moisture content. It can be performed by exploiting the Joule-Thomson expansion effect (self-refrigeration, Figure 2.13) or through a heat exchanger, exploiting a refrigerant fluid (external refrigeration, Figure 2.14). It is important to observe that generally, low temperature processes are used to separate water and natural gas liquids (NGL, mixtures of C_2-C_5 hydrocarbons) simultaneously from the gas.

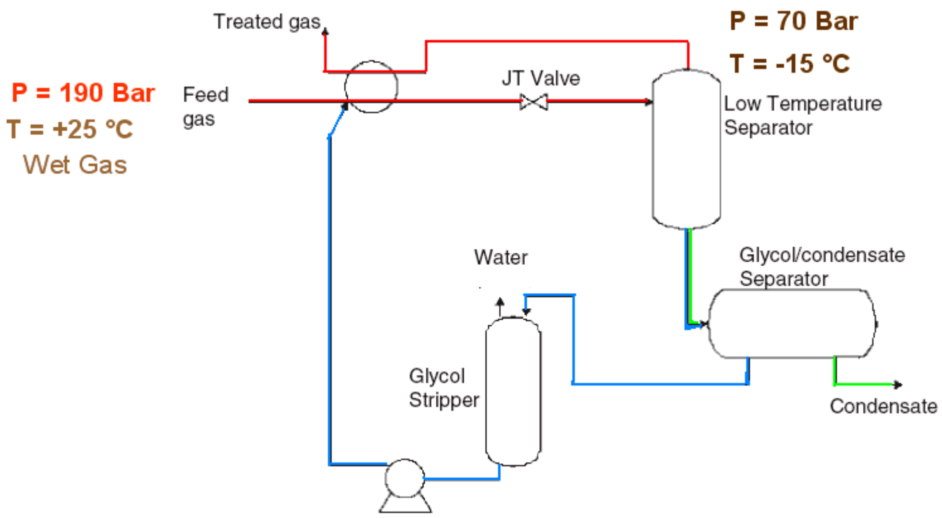

Figure 2.13: Dehydration unit with refrigeration by J-T expansion. Figure taken from [37] with modifications.

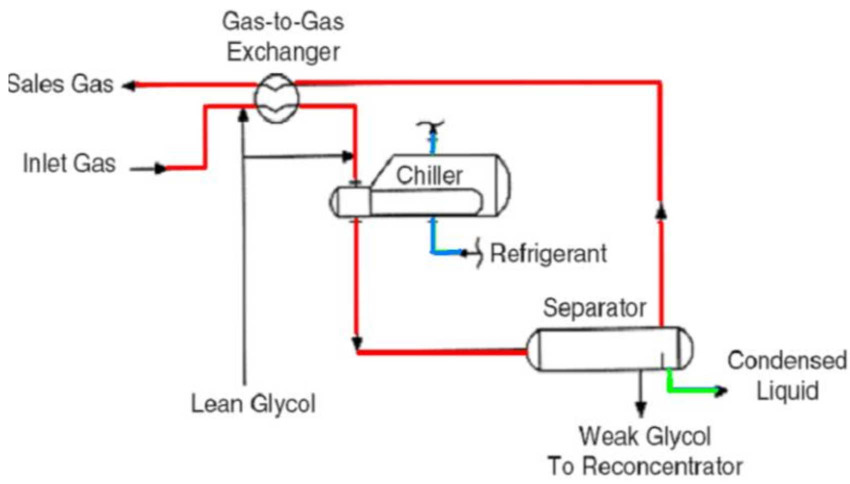

Figure 2.14: Dehydration unit with refrigeration by heat exchanger. Figure taken from [37] with modifications.

The selection among the available configurations may depends on several factors that must be taken into account case by case.

Table 2.4. Advantages and disadvantages of dehydration processes [37].

	Advantages	Disadvantages
Glycol process	- Lower installed cost - Lower pressure drop - Continuous rather than batch - Easy glycol make up - Handles lots of water - Simple maintenance - Require less regeneration heat per pound of water removed	- Water dew points below 25 °F require stripping gas - Glycol is susceptible to contamination - Glycol is corrosive when contaminated or decomposed
Solid desiccants	- Dew point as low as 150°F are obtainable - They are less affected by small changes in gas P and T - They are less susceptible to corrosion or foaming	- Higher capital cost and higher pressure drops - Desiccant poisoning by heavy hydrocarbons, H_2S, CO, etc. - Mechanical breaking of desiccant particles - High regeneration heat requirements and high utility costs - High space and weight requirements - Not suitable for very we gasses
Low temperature process	- Can meet pipeline specification for both for water and hydrocarbons dew point - Power consumption is minimal - Corrosion is minimal, especially if hydrate inhibitors are not used	- Unattractive when adequate wellhead pressure is not available - Strongly dependent of well flowing-tubing pressure, which evolves during reservoir exploitation - Difficult to control - Addition of hydrate inhibitors and use of external refrigeration increase both capital cost and operating expenses

	- Generally not suited to hot countries

2.2.3 Sweetening

As mentioned above, hydrates formation can be prevented not only through a dehydration process but also by removing other forming and promoting species with the sweetening process. Generally, the sweetening process aims to remove acid gases species such as sulfur compounds and carbon dioxide. The main sulfur compounds are H_2S, CS_2, COS. Particularly, H_2S removal is mandatory since it is toxic, flammable and extremely corrosive and it might cause catalyst poisoning and its combustion generates undesirable compounds (SO_x) which are one of the main reason for the formation of acid rains.
Carbon dioxide is nonflammable, thus large quantities are not desired in the final fuel. It results to be less acid than hydrogen sulphide, indeed the principal hazard of CO_2 is the exposure to elevated concentration (10 % *v/v*). Moreover, its removal is needed since it may cause an increase in downstream compression costs. H_2S and CO_2 are called acid gases since in presence of water, they form acids or acidic solutions which may be very corrosive.
The most common gas sweetening technology is the chemical reaction process, where H_2S and CO_2 are removed from the gas stream (*sour gas*) by a chemical reaction with a material in the solvent solution. It can be performed both by absorption (liquid desiccants such as amine solutions are used) and by adsorption (solid desiccants such as molecular sieves are used).
Also in this case, in both methods mentioned, a regeneration process to regenerate and re-use the saturated desiccant can be performed (desorption) by providing heat to the system.
Moreover, the extracted H_2S can be converted into elemental sulfur (a harmless chemical), through the Claus process, for producing H_2SO_4.
When the absorption method is selected, the sweetening process (Figure 2.15) starts with the incoming sour gas that flows through an inlet separator where solids and free liquids are first removed from the main gaseous stream. Most of the liquids are separated out by baffles, while in the upper part of the column (gas outlet) a mist extractor traps liquids entrained in the gas before it leaves the vessel. Certain sweetening units present also an outlet separator to further remove entrained liquids before the gas moves to other treatments or before the gas is sold. After the inlet separator, the sour gas flows to a contactor column where it comes in contact with the lean amine solution (countercurrent flow). The most commonly used columns for this application are tray columns, which as discussed for the dehydration process, presents bubble caps for ensuring a good contact between the phases. Generally, 20 trays are used: the higher the number of them, the higher the degree of separation. The liquid level is properly maintained on each tray by weirs on downcomers. The temperature of the lean amine has to be kept 10 °F warmer than the sour gas to avoid hydrocarbons condensation. Passing through the bubble caps, the rising gas streams form bubbles dispersed into the liquid hold up on the plate. On the other hand, the amine solution flows from the top to the bottom through the downcomer so that a counter current flow is performed. A mist extractor is placed at top of the column where the sweet gas finally exits the tower.
Other types of columns can be exploited for this application, such as the packed one (as described for the dehydration process). Acid gases can be effectively removed also by physical adsorption which, according to Henry's law, is able to remove the undesired components by increasing the pressure of the system. Nevertheless, these kind of applications are limited.

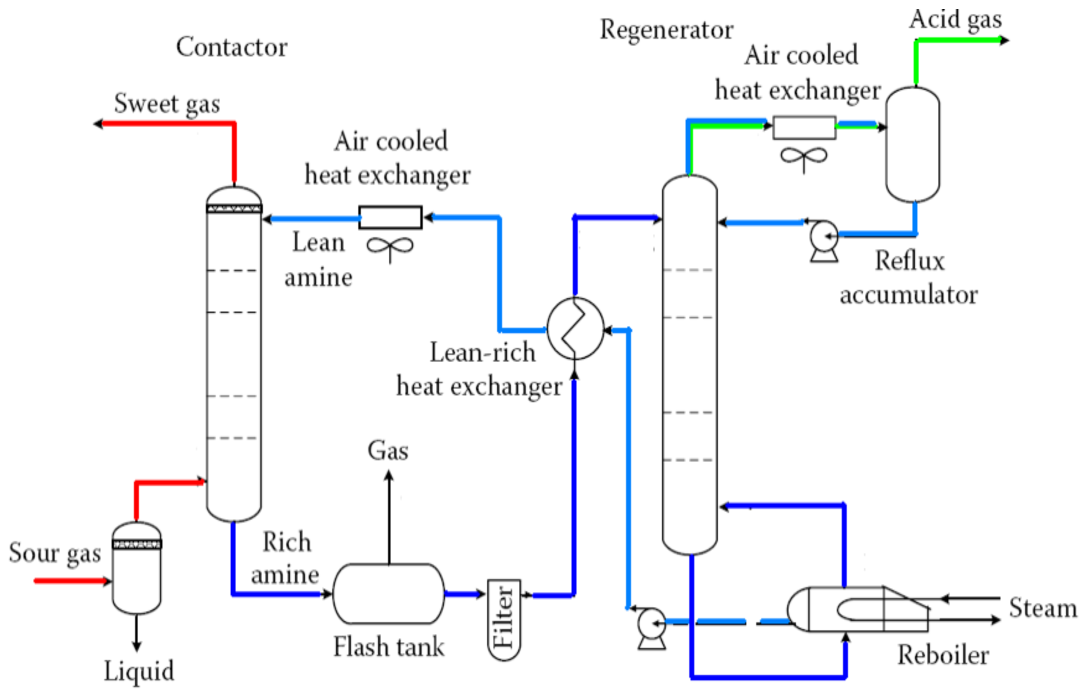

Figure 2.15: Schematic of a sweetening unit where an absorption process is performed. Figure taken from [38] with modifications.

As an alternative to absorption, adsorption can be performed. It implies the utilization of a solid desiccant such as zeolite due to its advantages: high specific surface, controllable pore dimension and basic behavior. Basicity is important since the aim of the process is adsorbing acid compounds, whereas pore size confers selectivity with respect to the dimension of the molecules which want to be adsorbed. In this configuration, the sour gas is fed into the column and it will exit purified of the acid gases (sweet gas). The regeneration is usually performed by sending part of the NG purified (5-10%) to the saturated column, after being heated up around 180-300 °C (deadsorption is an endothermic process) [39].

2.2.4 NGL recovery and fractionation

An additional phase in the NG processing is the natural gas liquid (NGL) recovery.
Raw NG streams, apart from methane, are associated with other hydrocarbons (i.e., ethane, propane, n-butane and pentane plus) called NGLs. These products have to be recovered due to their economic value: ethane and propane, for example, comprise more than 70% of all U.S. domestic production. Moreover, NGLs are separated from NG to maintain a proper heating value and dew point of hydrocarbons for a safe and economical transport through pipelines.
The choice of NGL recovery process is dependent of (but not limited to) the feed gas conditions. To extract NGLs from NG, different processes are available: absorption, adsorption, membrane and cryogenic processes [40].
The absorption process requires a high capital investment, mainly because of the large space required to operate using large heaters for the columns to supply the required energy. The adsorption process operates at high pressure to adsorb NGLs from NG in solid materials such as silica gel or activated carbon. The high pressure operation makes this process capital intensive. Membrane processes are compact in size and can achieve the desired efficiency with a smaller physical footprint and lower capital cost. On the other hand, these processes are relatively new in the gas industry and many further developments are in full swing to achieve a better efficiency and low operating and total costs with less process complexity.

Cryogenic distillation is a widely used technology for extracting NGLs from NG due to its high product purity and recovery. These processes are synergistically effective when integrated with liquefied natural gas (LNG) or nitrogen recovery unit (NRU).
Recent advancements in the conceptual design of NGLs have focused on improving the energy efficiency and product specifications and on decreasing costs through either a process integration or process intensifications. For instance Qyyum et al. [41] integrated the NGL process with the LNG and optimized it, with the result of 36,3% total annualized cost savings with a 1,38 year payback period.
The lean oil absorption technology is considered to be the oldest and least efficient process for NGL recovery and uses lean oil to absorb hydrocarbons from feed gas. Rich oil from the bottom is sent to the stripping unit to regenerate oil and separate the NGL. In the adsorption process, adsorbent media such as zeolites or activated carbons are used. Adsorption is considered an emerging technology for hydrocarbon separation, mainly because of low energy consumption and sustainability for small-scale NGL recovery plants. In the last years efforts have been made on the adsorbent materials in order to achieve a higher purity level.
The membrane separation process has been qualified as a suitable candidate, specifically for offshore plants, owing to its compactness, minimum utility requirement and low weight. In this process, the NG is passed through the membrane and hydrocarbons are removed while producing lean NG. Polymeric membranes are widely used because of their robustness and high selectivity. Lastly, the cryogenic process is typically used to extract NGL from NG with high purity and high recovery. In a typical cryogenic process, the feed gas is cooled and chilled in a series of heat exchangers and refrigeration cycles, and the chilled feed gas is then fed to the cryogenic distillation column (demethanizer unit). A methane-rich stream is obtained from the demethanizer unit (from the top), and the NGL stream is get from the demethanizer bottom. These NGL streams can be then fed to other columns for further fractionation (e.g., deethanizer, depropanizer). Advantages and limitations associated with absorption, adsorption, membrane and cryogenic processes for NGLs recovery are summarized in Tab. 2.5, while in Fig. 2.16 a schematic representation of them is showed.

Table 2.5. Advantages and disadvantages of NGL recovery process [40].

Technology	Advantages	Limitations
Absorption	- Able to remove light and heavy NGL - Low pressure drops - Removal of gases such as N_2	- Requires large equipment and physical spaces - High energy consumption
Adsorption	- High selectivity - Reliable	- High capital investment because of high pressure vessels
Membrane	- Simplest method - Cheapest process - Compact process	- Membrane fouling at high driving force - Concentration polarization - Difficult to control - Simulation of multicomponent gas mixture membrane process
Cryogenic	- High product recovery	- Complexity of control system - High energy consumption - All water must be removed to avoid hydrate formation

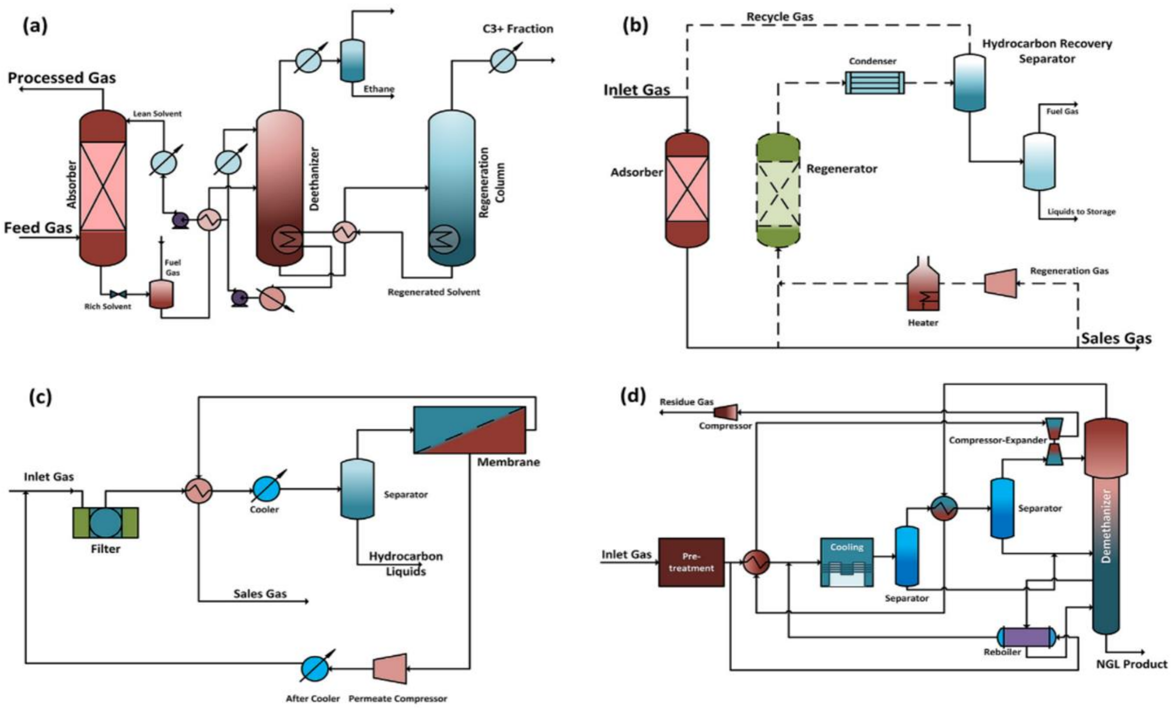

Figure 2.16: NGL recovery processes (a) absorption, (b) adsorption, (c) membrane and (d) cryogenic. Figure taken from [40] with modifications.

2.2.5 Gas reinjection

Another operation performed in the upstream phase of the O&G industry is the reinjection of (raw or treated) gases into the reservoir. It may be needed for several functions such as: maintaining the reservoir pressure, increasing oil production, sparing the necessity to handle the associated gas, reducing the adverse effect of production on the environment and preserving oil reserves for future utilization.

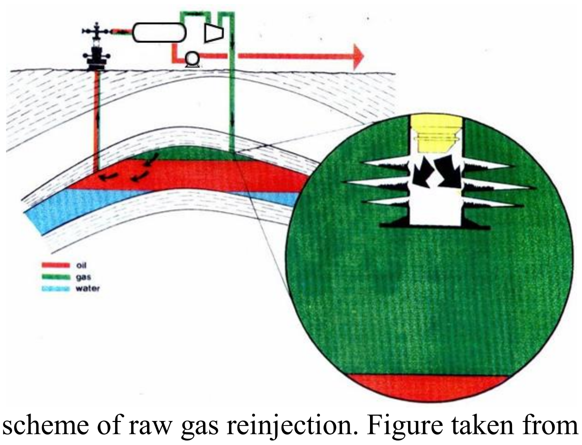

Figure 2.17: Simplified scheme of raw gas reinjection. Figure taken from [42] with modifications.

For instance, N_2 may be injected into the reservoir though a series of injection wells positioned to force the oil to the producing wells. Injection conditions are chosen such that nitrogen becomes miscible with oil phase. As the oil is produced, the nitrogen and associated gas are produced as mixed gas phases. The produced gas can be then reinjected or processed for fuel, sales gas and NGL production. Initially, little or no N_2 will be in the gas and oil produced, but inevitably it will break through and reach the producing wells. As the field becomes depleted, the nitrogen content increases. Eventually, the N_2 level reaches a point at which gas production

is no longer economically possible, and the project is stopped. Another type of gas that can be used for this purpose is CO_2. Carbon dioxide, essentially, scrubs the oil from the reservoir and can greatly increase oil production. As in the previous case, the CO_2 injected into the reservoir is produced with the oil and gas and it must be handled in the gas processing facilities.
The CO_2 that is injected into the reservoir is typically purchased from third party suppliers and it may represent the single greatest operating cost in the EOR project. Therefore, carbon dioxide produced with the associated gas is valuable and must be recovered and recycled to the reservoir.

2.3 Additional steps for the FLNG upstream stage

Over the past decades, it has become clear that significant quantities of NG reserves are not so conveniently located. For these stranded gas reservoirs utilizing a conventional production and processing system is not feasible (both for economic and technological reasons). The best candidates for remote offshore applications are floating liquefied natural gas (FLNG) facilities, which include additional steps in the upstream stage with respect to the ones required by the NG that does not have to be liquefied.
Therefore, FLNG facilities are employed for performing the conventional operations of production and processing (with the addition of several steps required by the liquefaction unit), liquefaction and storage.

2.3.1 Mercury removal and nitrogen rejection

One of the main difference between the conventional NG upstream stage and the FLNG, is the mercury removal unit. Mercury may be present in raw NG and, due to the downstream cryogenic operations (e.g., liquefaction), its removal from the gas stream is mandatory, since it may cause several damages to materials employed. For instance, mercury corrodes brazed-aluminum heat exchangers as it amalgamates with the aluminum to weaken the material. Moreover, elemental mercury attacks other metallic species such as copper, zinc and brass, chromium, iron, nickel. As a consequence, if the NG needs to undergo cryogenic processing, the mercury must be removed to levels below 0.01 $\mu g/Nm^3$ in order to avoid the aforementioned problems.
For removing mercury, two types of processes can be exploited and both of them take advantage of the reactivity of elemental mercury with a bed made of a selected material. The first option is a non-regenerative process where a chemisorption is performed. It uses sulfur impregnate on a support such as activated charcoal or alumina; mercury reacts with the sulfur to form a stable compound on the adsorbent surface. The second available process for this purpose is a regenerative process, where silver-impregnated molecular sieves are used to chemisorb elemental mercury while providing dehydration at the same time. The Ag-Hg amalgam decomposes at typical regeneration temperatures used in the dehydration step [43].

2.3.2 Liquefaction

NG liquefaction is an energy-intensive industrial processes due to the cryogenic temperatures needed to be reached. That is why, reducing the energy consumption, results to be mandatory in this application. It consists in cooling down NG to a temperature below -162 °C at ambient pressure. Liquefaction results to be mandatory for reducing the volume of the inlet stream by a factor of 600 and for obtaining a product with a very high energy density. These two factors allow and facilitate the transportation of higher volume of NG by trucks or cargos (LNG carriers). Liquefaction can be performed both, onshore and offshore. In particular, the different processes can be classified as: onshore large-scale, onshore small-scale, and offshore [6]. Each category requires a different attention.

For onshore applications, the most employed solutions include the cascade, the mixed refrigerant (MR) and the expander-based (EXP) processes. Whereas for offshore liquefaction, the single mixed refrigerant and nitrogen expansion processes have been considered to be the most promising options. It is important to take into account that for offshore applications, key factors such as safety, deck space and sensitivity to platform waving need to be considered.
In brief, LNG technologies are based on refrigeration cycles which involve four main steps: 1) compression of the refrigerant to a high-pressure, hot stream (compressor), 2) heat released from compressed refrigerant (condenser or cooler and heat exchanger), 3) expansion of the compressed refrigerant to a low-pressure, cold stream (valve or expander), 4) heat absorbed by the cold refrigerant (heat exchanger). The latter step is where the cooling duty is provided to the natural gas.
Reviews in technical reports show that the MR process dominates the LNG industry, but has competition from the cascade process in large-scale applications, and from the EXP process in small-scale and offshore applications.
Starting from the onshore case, as mentioned, the main processes used are: cascade liquefaction, MR liquefaction and EXP liquefaction (Fig. 2.18).

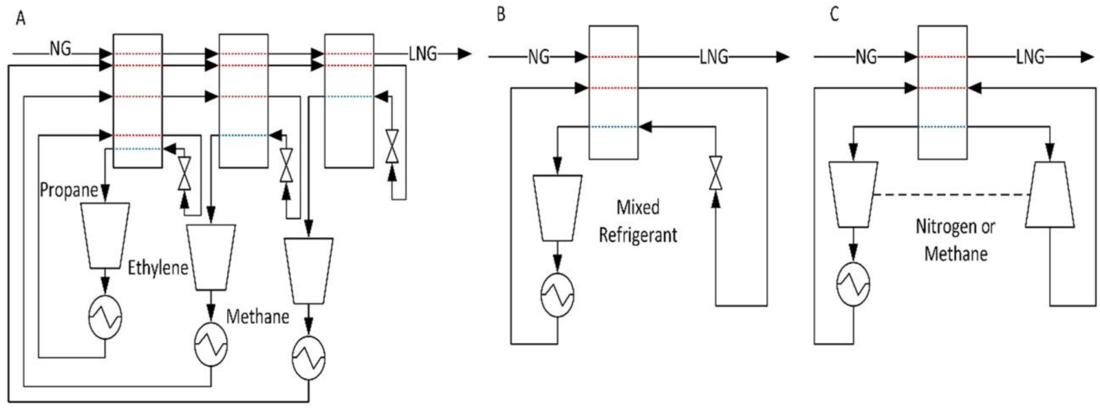

Figure 2.18: Schematic overview of three liquefaction technologies (A = cascade, B = mixed refrigerant, MR and C = expander-based, EXP). Figure taken from [6] with modifications.

Regarding the cascade type, despite it is not the most used one, it results to be attractive due to its high thermal efficiency (the highest among the three methods listed) and low energy consumption. Nevertheless, it is characterized by a complex infrastructure that leads to the highest capital cost because of the large number equipment involved.
As can be observed from Fig. 2.18, the process comprises three independent pure refrigeration cycles that present different boiling temperatures in order to provide refrigeration capacity in different temperature ranges. The first employed refrigerant is propane. In its refrigeration cycle, propane is pressurized to a high pressure by a multi-stage compressor system and then cooled down using an air/water cooler. The condensed propane produces refrigeration capacity by reducing its pressures in throttling valve. Then the low-temperature propane is used to cool NG and the other two refrigerants to temperatures around -30°C. Then, in ethylene refrigeration cycles, pre-cooled ethylene provides the cooling capacity to cool NG and methane to -90°C. Finally, in methane refrigeration cycle, methane is used to liquefy NG at -160°C.
The MR liquefaction process is the one which has received most attention, since it has been designed to reduce the amount of the equipment compared to the cascade liquefaction process. While the previous process is composed of three different refrigeration cycles, in the MR, only one cycle is present. It consists of a continuous cooling of the NG stream by using a mixture of light hydrocarbons (including methane, ethane, propane, i-butane, n-butane, i-pentane, n-pentane, ethylene and nitrogen). The mixed refrigerant is carefully selected with aim of

minimizing the gap between the cold composite curve and the hot one in the multi-stream heat exchanger.
Figure 2.19 shows the cooling curves of cascade, MR, and EXP. Since cascade uses multiple refrigerants, it has several cooling temperature levels which allow for small temperature differences between the hot and cold sides of heat exchangers. On the other hand, MR can mimic the NG cooling curve by using a refrigerant consisting of a carefully selected mixture of hydrocarbons. As a result, the energy consumption of mixed refrigerant liquefaction process is significantly low, but on the other hand it requires more heat-exchange surface area.

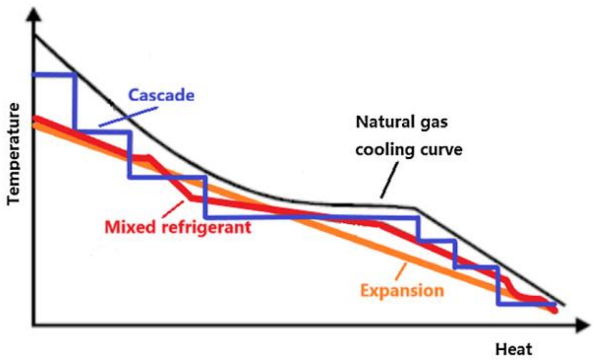

Figure 2.19: Cooling curve of cascade, MR, EXP. Figure taken from [6] with modifications.

MR liquefaction process can be classified into three typical types, namely single mixed refrigerant liquefaction process (SMR), dual mixed refrigerant liquefaction process (DMR) and pre-cooling mixed refrigerant liquefaction process. SMR liquefaction process is suitable for middle-scale and small-scale LNG plant due to its low cost and simplicity. In this case, the mixed refrigerant is pressurized by two-stage compressors and then enters a vapor–liquid separator. The vapor phase refrigerant is subsequently compressed in the compressor. The liquid phase of the refrigerant is pumped to the same pressure. Then, vapor phase and liquid phase refrigerant mix together and cool in the water cooler. The pressurized mixed refrigerant is cooled down to approximately −160 °C in the multi-stream heat exchanger and then reduce its pressure in the expansion valve to produce refrigeration capacity. The cooled mixed refrigerant is used to cool both NG and the warm mixed refrigerant.
The dual mixed refrigerant liquefaction process utilizes two independent mixed refrigerant cycles to liquefy NG. The first mixed refrigerant cycle, with heavier mixed refrigerant (ethane, propane, i-butane and n-butane, etc.), is used to pre-cool the NG and the lighter mixed refrigerant. The lighter mixed refrigerant (methane, ethane, propane, and nitrogen, etc.) is used to liquefy and sub-cool the NG. Due to the existence of the pre-cooling cycle, DMR liquefaction process has a higher thermodynamic efficiency than the SMR one.
Finally, pre-cooling mixed refrigerant liquefaction process is widely used in base-load LNG plant. Its energy efficiency has a great impact on the operation cost of base-load LNG plants. Propane pre-cooling mixed refrigerant liquefaction process (C3MR) is the most well-established pre-cooling mixed refrigerant liquefaction process. In particular, APCI (Air Product Chemical Inc.) C3MR has been dominant in baseload LNG plant market since it was developed. It includes two refrigeration cycles: the first one is a three stage propane pre-cooling refrigeration cycle, whereas the second one is a mixed refrigerant refrigeration cycle. The propane cycle cools the NG and mixed refrigerant to -30°C. The existence of propane pre-cooling cycle is useful for eliminating the big temperature difference at the warm end of the exchanger.
In EXP, pure nitrogen or methane is used as the refrigerant. These refrigerants can reach the low temperatures needed for the liquefaction of NG in a single loop, but the main drawback of

this operation is a lower efficiency compared to those of cascade and MR. Nevertheless, for reducing the energy consumption, the EXP process recovers part of the compressor work by replacing the throttling valve with an expander.
Expander based liquefaction process is a kind of reverse Brayton cycle utilizing turbo-expander to generate refrigeration capacity. The common expander based liquefaction processes include nitrogen expansion liquefaction process, nitrogen–methane expansion liquefaction process and NG open expansion liquefaction process. Due to the simplicity of process configuration and quick start-up and shut-down, expander based liquefaction process has been considered as the suitable liquefaction process for middle-scale or small-scale LNG plant.
Due to lack of area on vessel's decks, the selection criteria of liquefaction process for FLNG facilities is different compared to onshore LNG plants. The main concerns for an offshore NG liquefaction process are simplicity and small amount of equipment in order to reduce the space required for LNG liquefaction. Therefore, MR liquefaction process and EXP based liquefaction process are considered as a suitable process for offshore LNG production. As a summary, Table 2.6 shows advantages and disadvantages for the three main LNG technologies presented.

Table 2.6: Advantages and disadvantages of LNG liquefaction technologies [6].

Criteria	Cascade	MR	EXP
Application	Onshore large-scale	Onshore large scale, small-scale, offshore	Onshore small-scale, offshore
Energy efficiency	High	Medium to high	Low
Equipment count	High	Low to medium	Low
Heat-transfer surface area	Medium	High	Low
Simplicity of operation	Low	Low to medium	High
Ease of start-up and line-up	Medium	Low	High
Adaptability of feed-gas compositions	High	Medium	High
Sensitivity to ship motion	High	Medium to high	Low
Space requirement	High	Medium	Low
Hydrocarbon-refrigerant storage	High	Medium to high	None
Capital costs	High	Low to medium	Low

2.3.3 LNG storage

Following the production and processing chain of a FLNG plant, after the liquefaction phase, NG must be stored and kept to the liquefaction conditions (and effective insulation is mandatory). The storage occurs not only on the facility, but also on the LNG carrier, which allows the transportation of LNG to the receiving terminal. Specific storage systems have been developed for these purposes [10].
The fundamental difference between LNG carriers (and FLNG storage systems) and other tankers is the cargo containment and the handling system. In general, there are three different LNG containment systems: two freestanding solid type structures and one non-freestanding (membrane) type design.
The freestanding (or independent tanks) are self-contained, usually spherical or prismatic in shape and made out of aluminum alloys or 9% nickel steels with layers of insulation on the

outside (Fig 2.20). Independent tanks are completely self-supporting and do not form part of the ship's hull structure. Moreover, they do not contribute to the hull strength of a ship. The tanks are welded to cylindrical skirts or otherwise tied to supporters that are welded to the ship structure.

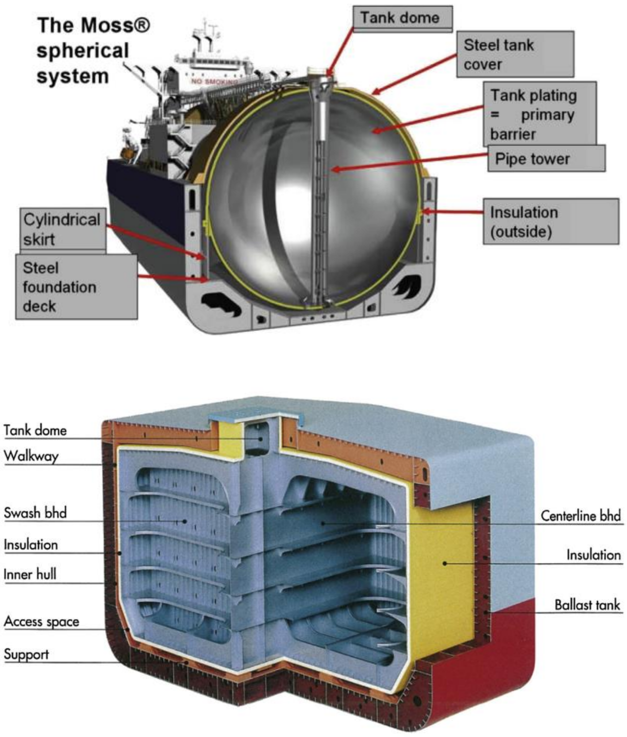

Figure 2.20: Schematic of freestanding tanks. Figure taken from [10] with modifications.

On the other hand, membrane tanks are non-self-supported cargo tanks surrounded by a complete double hull ship structure. The membrane containment tanks consist of a thin layer of metal (primary barrier), insulation, secondary membrane barrier, and further insulation in a sandwich construction (Figure 2.21). The membrane is designed in such a way that thermal and other expansions or contractions are compensated without undue stressing of the membrane. With the membrane design, the ship's hull, in effect, becomes the outer tank. Insulation is installed thereon, and a membrane is placed on the inside to retain the liquid. Possible compositions of the inner surface of this "double hull" are for example either high nickel (36%) steels (Invar), or 18% chromium and 8% nickel stainless steel.

Figure 2.21: Schematic of a membrane tank. Figure taken from [10] with modifications.

As all cargo tank system designs have proven safe and reliable in service, the choice of cargo tank design is primarily based on prices, delivery schedule, and shipyard availability rather than technical or performance criteria. Over the last years there has been a clear move toward membrane-type carriers, because membrane tanks utilize the hull shape more efficiently, thus have less void space between the cargo tanks and ballast tanks. More than three quarters of the new LNG ships constructed in the decade 2001 to 2011 were of the membrane design due to their cargo capacity and capital cost advantages. However, self-supporting tanks are more robust and have greater resistance to sloshing forces, which is an important design consideration for offshore storage. Table 2.7 gives the comparative characteristics of different LNG containment systems.

Table 2.7. Comparative characteristics of LNG containment systems [10].

Characteristics	Prismatic freestanding	Spherical freestanding	Membrane tanks
Safety in event of vessel grounding/collision or other emergency	Compared with membrane system less likelihood of hull damage being transmitted to cargo tanks. More efficient use of cubic space	Safest system in event of grounding or collision-tank structure independent of hull and most void space between vessel hull and cargo tanks. Spherical tanks can be pressurized for emergency discharge in case of cargo pump failure	Damage to hull of vessel may be more easily transmitted to tank structure than with freestanding tanks. Membrane systems are also more liable to damage or puncture due to causes such as surging of cargo in tank and entry of tank for inspection or repair.
Reliability of containment system	Most ship years' operating experience and most experience without primary barrier failure. Structure can be analyzed and risk of fatigue failures minimized. Tanks can be constructed and 100% inspected prior to installation in vessel.	Tank system easiest to analyze structurally; therefore can be made most reliable.	Structure cannot easily be analyzed and therefore difficult to assure absence of fatigue failures. This could potentially lead to costly off-hire and repair time over the project life

2.3.4 Marinization implications

The term marinization is used to describe engineering-based modifications to equipment (in some cases of process parameters as well) that are normally used in onshore process plants to make them workable in offshore and mobile conditions. The ship motion affects the process performance and it is the result of factors such as waves, current, wind and ship geometry. The Mechanical integrity of equipment is compromised as well, since the ship motion induces sloshing of the fluid content that may lead to early mechanical failure of internals as well as increase structural fatigue. Therefore, the design phase of a FLNG facility has to take into account all these factors both in a normal operating conditions and in extreme ones. The most affected pieces of equipment are the tallest items and the ones with high liquid inventory. For example, horizontal separators, columns (i.e. AGRU unit) and liquefaction units are considered among the critical equipment.

Horizontal separator is a critical item due to its normal high liquid inventory, which is subjected to sloshing. This equipment should be oriented along the longitudinal axis in order to minimize the impact of motion. Moreover, anti-sloshing baffles are used for the same reason. The placing of level measuring instruments is also important because vessel end position changes with respect to the liquid level and, as a consequence, level readings.

Absorber and stripper columns are critical equipment in FLNG plants. Tilting of the column affects the liquid flow, and as a consequence there is an insufficient contact between gas and liquid phases (hence compromising mass transfer phenomena). Indeed, gas bypass area increases with inclined angle and bed height. Approaches for reducing the impact of liquid mal-distribution are: use of structured packing, use of more number of beds with lesser height, static tilt to be reduced to a minimum and use of special designed distributors.
Similar to column-based unit operations, liquefaction unit performance is highly affected by ship motion. Liquid mal-distribution in shell side, due to motion, triggers underperformance of exchangers. On the other hand, motion has less impact on tube side flow. Also in this case, cautions for limiting these bad effects have been though. For example impact on mal-distribution is high with high number of transfer unit, NTU. Therefore, an exchanger with high NTU (tall exchanger) can be divided into two or more exchanger with lower NTU each.

2.4 NG midstream and downstream stages: NG vs LNG

As introduced, the supply chain of NG involves three main steps (Fig. 2.22). The first one, is the one previously described, namely the upstream phase, in which NG in produced and processed (the processing phase is slightly different in the case of LNG or NG due to the different quality specifications required by the liquefaction process). Following the upstream phase, the midstream one occurs. In this step of the chain, NG (or LNG) is transported from the production point to a receiving terminal. The last stage of the chain is the downstream one, which concerns the NG storage and consequent distribution to the end user by the national transmission system.

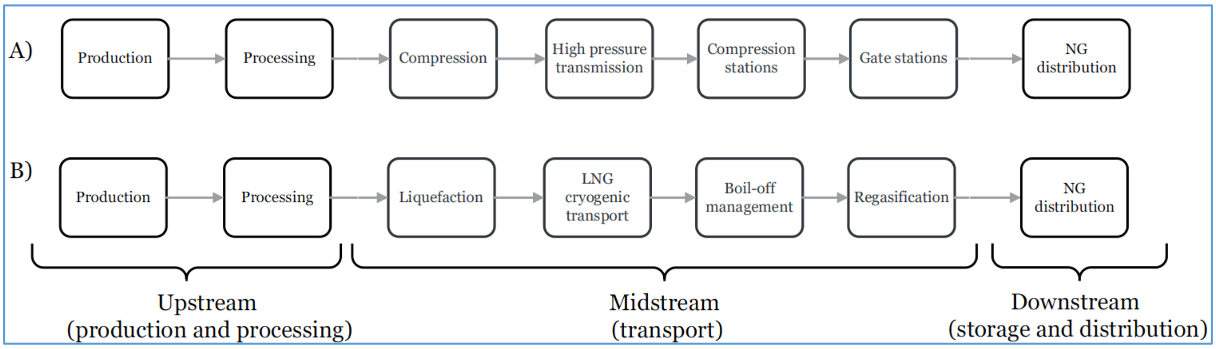

Figure 2.22: Simplified block diagram of the NG supply chain for A) traditional pipeline supply and B) LNG. Figure taken from [7] with modifications.

2.4.1 Transportation

Following production and processing phases, NG (or LNG) needs to be transported. When in its gaseous form, NG is transported through pipelines. An initial compression stage is necessary for the high-pressure transmission in pipelines. Nevertheless, eventual compressor stations are strategically installed along the gas transmission lines to maintain the operative pressure and assure NG transmission [44]. Typically, compression stations are composed of several compressor units connected either in series or in parallel which aim to increase the pressure of NG, providing the required force to keep it moving along the line. More precisely, a compressor station is a large mechanical facility that receives the gas at pressures ranging from 200 psi to 600 psi, and compresses it back up to 1000 psi to 1400 psi. As a result, NG can overcome frictional losses and maintains required pressures to keep moving through the transportation line towards another compressor station. Afterwards, the distribution phase, consisting in a pressure reduction for meeting the end-user needs, occurs.

In general, when the production and processing facility is offshore, a unique compressor station is employed: installation, management and maintenance of these components result to be prohibitive if conducted undersea. On the contrary, when the transmission system is onshore, more than one compression station is envisaged. Finally, gate stations are required to carry out the pressure reduction (if needed) for the distribution to the end-user.
When NG is transported by pipelines, fugitive methane emissions occur and it is mandatory to take them into account, due to their intensive environmental impact. Indeed, despite methane residence time in the atmosphere is lower compared to the CO_2 one, its environmental impact is sensitively higher: one ton of CH_4 is estimated to have the same impact of 27-30 tons of CO_2 in the atmosphere over 100 years [45].
NG losses in pipeline systems mainly occur at junctions between sections and pneumatic devices (i.e., compressors, valves). As an example, [46] reports estimation of leakages rates of long-distance pipelines in different regions.
In the LNG case, the transportation phase results to be extremely different since the product to be transported is not gaseous but liquid. Once again, following the liquefaction phase (both for the LNG and FLNG scenario), LNG is transported from the facility to a receiving terminal, where storage and regasification occur. LNG carriers are tank ships designed with the purpose of transporting LNG. They are specialized ships with insulated double-hulled tanks designed to contain the cargo slightly above atmospheric pressure at a cryogenic temperature (-169 °C approximately). Despite of the insulation system designed, it is not possible to prevent all external heat from reaching the LNG, thus some liquid boils off during the transportation and they deserve a proper management. The boil-off gas (BOG), typically at the rate of about 0.10% to 0.15% of the ship volume per day, must be removed to keep the ship's tanks at a constant pressure. The boil-off gas can be used as fuel in dual fuel engines or burned in the boilers to produce steam or it can be re-liquefied and returned to the cargo tanks, depending on the design of the vessel.
Due to the LNG and FLNG growth, maritime developments for the construction of bigger and better LNG carriers has been prompted. For example, one of the biggest LNG carriers in the world are the Q-Max Ships, operated by Qatar Gas. The Q-max ships are around 354 meters long and 55 meters wide and the LNG tankers use a type of membrane technology that ensures maximum efficiency. The fourteen ships owned by Qatar Gas have a total LNG capacity between 263.000 to 266.000 m^3. The Q-Max ships are known not only for their size but also for their advanced features: their engines burn significantly fewer amounts of fuel compared to conventional carriers, hence producing 35% lesser carbon emissions. Moreover, another novel feature is the non-carbon fire-extinguish system, the first of its kind to be used in an LNG carrier. Thus, these carriers have drastically reduced the transportation costs according to [47].

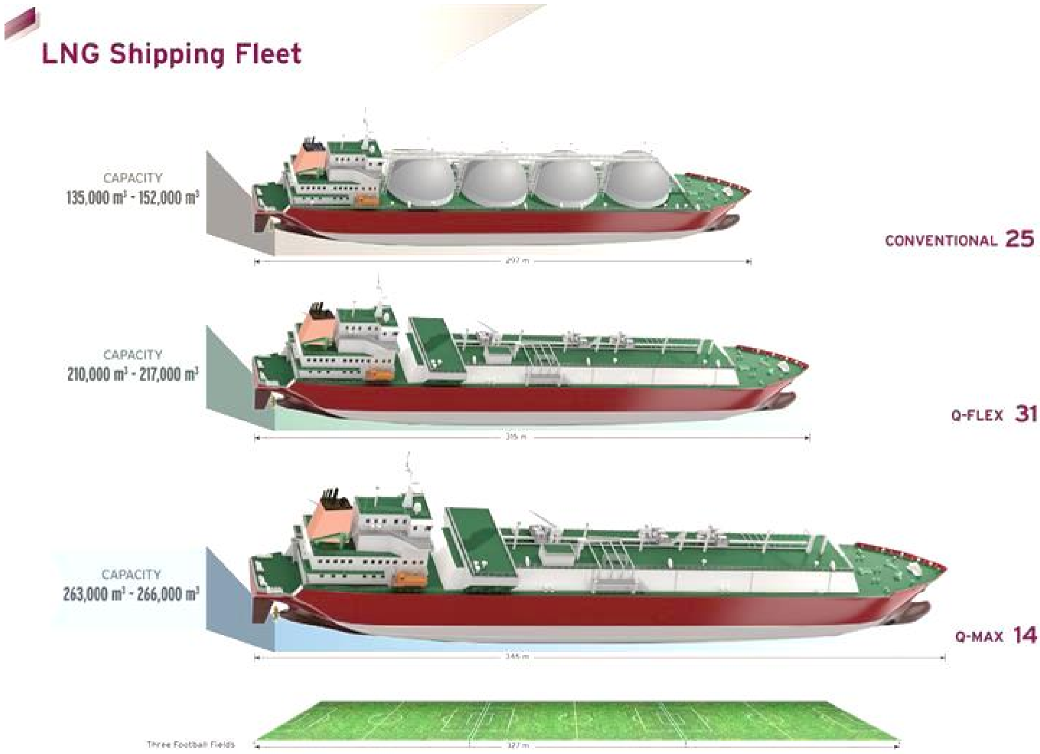

Figure 2.22: Examples of LNG carriers. Figure taken from [48] with modifications.

2.4.2 Receiving terminals: LNG and NG storage

When NG reaches its destination is not always needed right away and, fortunately, it can be stored. Storage ensures that adequate supplies of NG are available for seasonal demand shifts and unexpected demand surges. In addition, gas storage is also used by industry participants for commercial reasons: storing gas when prices are low and withdrawing and selling it when prices are high. Moreover, it serves as insurance against any unforeseen accidents, natural disasters, or other occurrences that may affect the production or delivery of NG. Both NG and LNG require proper storing infrastructure and management strategies.

LNG is unloaded from the transporting ship by means of pumps and then stored at atmospheric pressure in double-walled, insulated tanks that are designed for storing the liquid product at cryogenic temperatures. The insulation, like for LNG carriers and FLNG storage tanks, is designed to minimize heat gain and reduce product losses due to BOG. LNG storage tanks of various designs are available on the market. Selection of LNG tanks is project specific. They should address site conditions, design criteria, safety, geological considerations, environmental requirements, and applicable design, codes, and regulations. There are two main types of LNG storage tanks: in-ground storage tanks and above ground storage tanks.

An in-ground tank consists of a stainless-steel membrane, supported by rigid polyurethane foam insulation (Figure 2.23). This, in turn, is supported within a reinforced concrete caisson. The roof consists of a dome-shaped carbon steel structure supporting a suspended deck with glass wool insulation. In-ground tanks are less visible in their surroundings and more secure from a security standpoint. There is no risk of spillage with this high-integrity storage design. It is also more earthquake-proof as the seismic motion is not amplified in the underground tanks compared to the aboveground counterpart. With the earth berm, the tanks can be located close to one another, which is an advantage where land and space are limited.

The record for the largest LNG tank in the world was first set by an in-ground tank (200,000 m^3), although several aboveground tanks have recently been built with a similar capacity. These tanks are more expensive and take longer to build than aboveground tanks (about 4 to 5 years compared to 3 years for a tank built above ground).

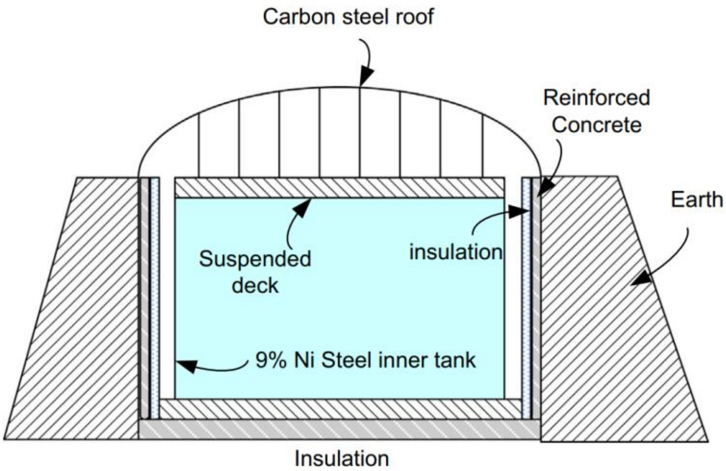

Figure 2.23: Schematic of an in-ground LNG tank. Figure taken from [10]with modifications.

Aboveground LNG tanks have two layers of containment. The primary containment is provided by the inner tank, which holds the LNG. Secondary containment is provided either by the use of dykes, berms, and impoundment dams around storage tanks, or by building a second tank around the primary storage tank to contain the LNG, which will protect against failure in the primary tank. All LNG storage tanks are constructed with thermal insulation to minimize heat transfer, reduce boil-off vapors, and protect the carbon steel materials from reaching cryogenic temperatures. The containment system is designed in compliance with LNG codes and standards, which provide guidelines for material selection and design requirements for LNG storage tanks and other equipment at LNG facilities. There are basically three tank types used for onshore terminals: single, double and full containment tank (Fig. 2.24-26).

Single containment tanks (Fig. 2.24) involve greater land requirements than the other tanks because of the separation distance between the tank and the bund wall. This type of tanks is the lowest cost option, which has been successfully used in the past. However, because it is more prone to external hazards than other types, insurance premiums are typically higher than the full containment, which penalizes the cost advantages.

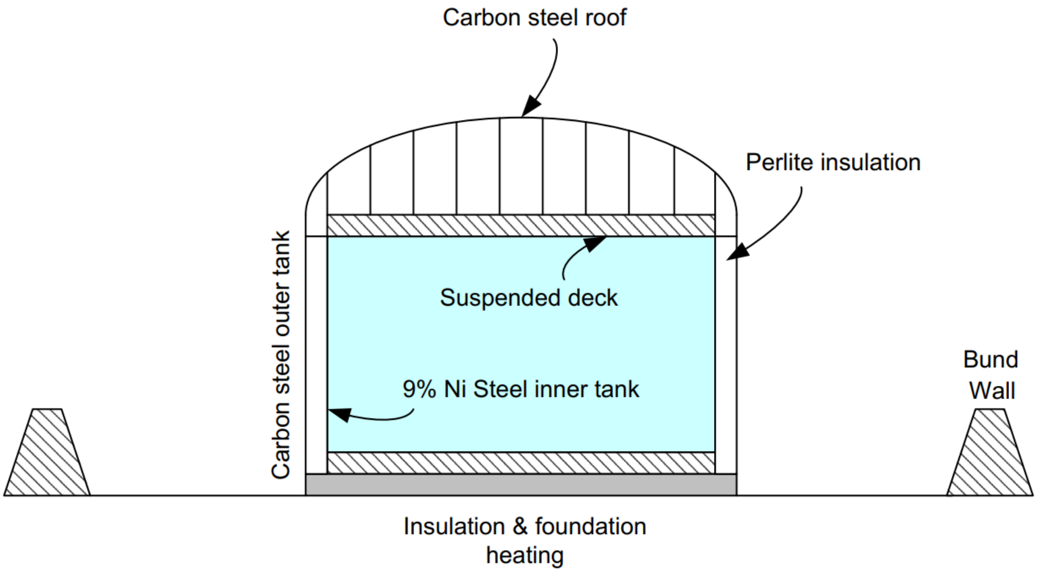

Figure 2.24: Schematic of a single containment LNG tank. Figure taken from [10] with modifications.

The double containment tank (Fig. 2.25) is similar to a single containment tank, with the addition of constructed walls as the secondary containment instead of a containment dyke. Therefore, if the inner tank fails, the secondary container is designed to contain the cryogenic liquid. The outer concrete wall increases the cost of the tank, but less space is required because the containment dyke is no longer necessary.

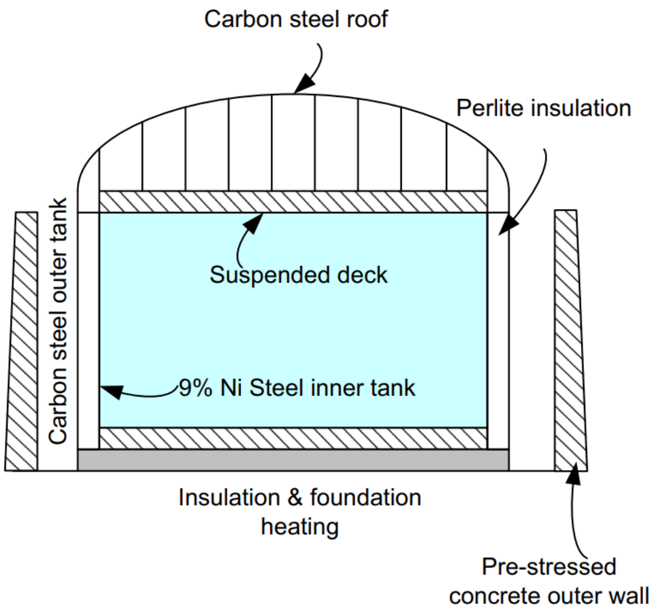

Figure 2.25: Schematic of a double containment LNG tank. Figure taken from [10] with modifications.

A full containment tank (Fig.2.26) is a double containment tank in which the annular gap between the outer and inner tanks is sealed. The majority of LNG storage tanks built in the last 10 years worldwide have been designed as full containment tanks. Full containment tanks cost from 10 to 20% more than single containment tanks. However, this type of storage has the advantage of an additional layer of safety against external elements such as fire, blasts, and atmospheric impacts. The full containment tank design is very compact and is currently the acceptable selection for most projects where land availability, location, local regulations and/or security do not permit the use of a single-containment design.

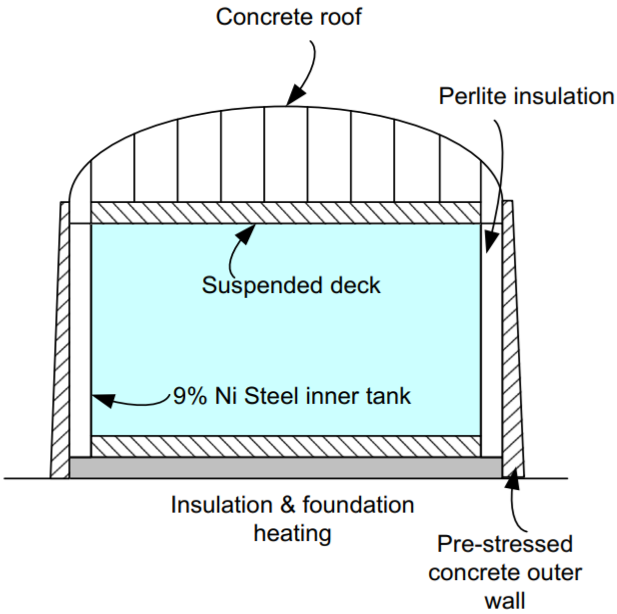

Figure 2.26: Schematic of a full containment LNG tank. Figure taken from [10] with modifications.

Also in the case in which it is not liquid but in its gaseous phase, NG needs to be stored and it can occur in several different ways. Nowadays, NG is most commonly held in inventory underground under pressure in three main types of facilities [49]: (1) depleted reservoirs in oil and/or natural gas fields, (2) aquifers, and (3) salt cavern formations. Moreover, as for the LNG, NG can be stored in above-ground storage tanks, which used to be the conventional method of storing coal gas in the early-to-mid 20th century.
The latter may be the solution when there are no regional underground storage facilities or if it is more convenient, because of the lower volume of gas to be stored. In the case of above-ground storage, the gas is stored in specially fabricated tanks which do allow for easy access to the gas and complete control of gas extraction from storage. However, while the costs for above-ground storage options are typically less than underground, tanks can store only a fraction of the NG that underground caverns can.
A gas holder (also called a gasometer) is a large container in which NG can be stored at or near atmospheric pressure and at ambient temperature. The benefit of using a gas holder (although possibly limited in storage capacity) is that it can store gas at district pressure and can provide extra on-site gas very quickly and at peak times. Furthermore, the gas holder is the only storage method that can maintain the gas at the required pressure, which is the pressure required in local gas lines, and thus it may hold a large advantage over the other methods of storage.

2.4.3 Regasification

As mentioned, LNG carriers deliver LNG to receiving terminals, where the liquid product is stored and transformed back into gaseous NG. Once regasified, the NG is delivered into the distribution pipelines in order to reach the end-user.
Since a large amount of heat is needed for vaporization of LNG, seawater, ambient air or other heat sources can be used together with waste heat from other industrial sites. The optimum choice of a LNG vaporization system is determined by the terminal’s site selection, the environmental conditions, regulatory limitations and operability considerations.
The regasification technology consists of a special heat exchanger in which a specific fluid (e.g., water or air) circulates in order to heat LNG and reach the gaseous form.

Nowadays, the most used types of vaporizers in regasification terminals are: Open Rack Vaporizers (ORV), Submerged Combustion Vaporizers (SCV), Ambient Air Vaporizers (AAV), Shell and Tube Exchange Vaporizers (STV) and Intermediate Fluid Vaporizers (IFV). According to statistics of LNG receiving terminals, 70% use ORV and Super-ORV, 2% use SCV and 5% use IFV (Fig.2.27).

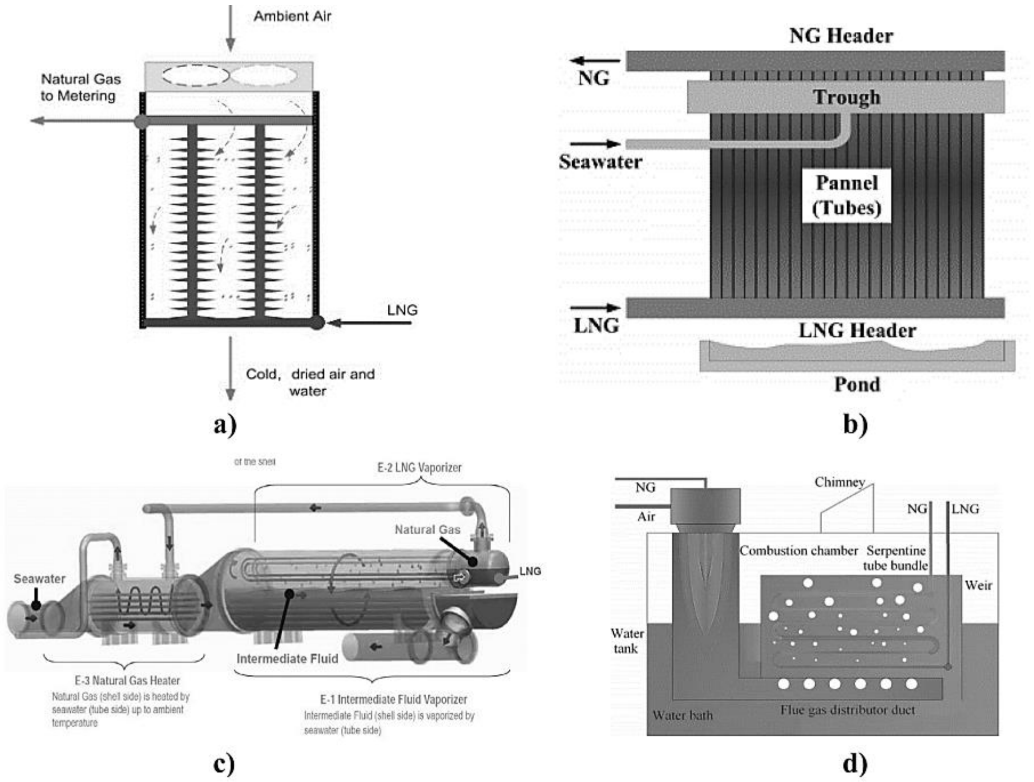

Figure 2.27: LNG vaporizers: a) AAV; b) ORV; c) IFV; d) SCV. Figure taken from [50] with modifications.

AAV is suitable in those places with warmer ambient temperatures, and it is mainly used in peak shaving plants. The main heat source of AAV is the energy extracted from the ambient air. The heat is absorbed directly from the surrounding air to heat the LNG by natural convection. A typical AAV design configuration consists of long parallel or in serial fin tubes, that could allow air to exchange heat over a large area. Principle of vaporization process starts when LNG is vaporized directly with air passing through a number of interconnected tubes and then the air condenses and freezes forming frost. Nevertheless, frost is poor conductor, and its generation reduces heat transfer coefficient which indicates effectiveness of vaporizer. Therefore, the vaporization of AVV depends on frost growth and its deposition on the vaporizer wall, since it causes limitation of working conditions.
ORV is a type of commercial heat exchanger widely used in large regasification plants for base load LNG receiving terminals. The mechanism of vaporizer is heat transfer tubes in which LNG flows from the bottom to the top inside the tube, whereas seawater flows from the top to the bottom outside the tube. The water spray equipment is installed on the top of vaporizer, which facilitates forming a uniform liquid falling film along the tube outside the heat transfer tubes. The LNG is circulated in tubes and it extracts heat transferred from seawater. The type of tubes is selected in this vaporizer with ribs, which are important for heat transfer area. The main challenge of this vaporizer is the heat transfer characteristics of the supercritical fluid flow inside the ribs tubes, which are different from that of a smooth tube. The improved type of vaporizer is Super-ORV, which also uses the sensible heat of seawater, but has different

configuration of the heat transfer tube comparing with ORV. This new type of Super-ORV is characterized by heat transfer tubes with double tube structure at the lower part.
IFV is a shell-and-tube vaporizer, which uses an intermediate fluid that circulates by the gravitational force in the system. Before starting work, intermediate fluid is evaporated by a heating source in the evaporator, then it is sent to transfer heat to LNG. After LNG heating, the intermediate fluid is cooled and condensed. A typical IFV is composed of a condenser, an evaporator and a thermolator, similar to a combination of three shell-and-tube heat exchangers. The heat transfer process of intermediate fluid occurs on the shell-side in which it transfers heat to LNG inside the tube. For this application, the intermediate fluid selection has to be considered according to these criteria: a sufficient latent heat, environmental regulations such as ozone depletion potential (ODP) and GWP.
SCV system requires approximately 1.5% of the total vaporized LNG as fuel [10], which adds a significant operating cost to the terminals. For this reason, SCVs are used only where no other free heat source is available. The SCVs can also be designed to utilize boil-off gas. In a SCV, LNG flows through a tube coil fabricated from stainless steel that is submerged in a water bath. Water in the bath is heated by direct contact with hot effluent gases that exit a submerged gas burner. The unit is compact and does not require large tracts of real estate for installation. Exhaust gases from the burner are sparged into the water through a distributor located under the heat transfer tubes. This causes rapid circulation of water through the tubes resulting in a very high thermal efficiency (over 98%) and high heat transfer rate. Agitation from the sparging action also prevents deposits or scale to be buildup on the heat transfer surface of the tubes. Since the water bath is always maintained at a constant temperature, the system copes well with load fluctuations and can be quickly started up and shut down. The controls for the submerged combustion vaporizers are more complicated when compared to the ORV. The SCV has more pieces of equipment, such as the air blow, sparging piping and the burner management system. These units are reliable and have very good safety records. Gas leaks can be quickly detected, and the unit can be safely shut down. There is no danger of explosion, since the temperature of the water bath stays below the ignition point of NG. The bath water is acidic as the acid gas content in the exhaust gas is condensed. Caustic is added to the bath water to control the pH value to protect the tubes against corrosion. The excess combustion water must be neutralized before being discharged to the open water system.
As a summary, Table 2.8 shows a comparative analysis of the different LNG vaporizers mentioned.

Table 2.8. Comparative analysis of LNG vaporizers [50].

Type	Environmental friendly technology	Construction cost	Technological simplicity	Maintenance	Operation cost	Capture of LNG cold energy
AVV	Low	Low	Simple operation	Low	Low	No
ORV	Medium	High	Simple operation	High	High	Possible
IFV	Medium	High	Complex technology	High	Low	Yes
SCV	High	Low	Need to observe	High	High	Possible

It is interesting to note that regasification of LNG releases a significant potential of cold energy, equivalent to 200 kWh of electricity per ton of LNG: regasification of LNG is the process with the highest potential for energy recovery.

Therefore, though the liquefaction process is quite energy demanding, the application of various energy recovery technologies in the regasification process may make it possible to recover a significant part of the energy used.
Indeed, the recovered energy, which can be either in the form of heat or cold, can be used in power generation and thus, it increases the efficiency of power production.
Nevertheless, literature studies concluded that most of the LNG regasification plants and facilities worldwide do not recover the cold during the LNG regasification, which means that the great amount of energy supplied to LNG during the energy-intensive liquefaction is wasted. The global potential of possible cold production from LNG was identified as nearly 12 GW. However, nowadays, the cold production utilizes less than 1% of the regasification global potential. This is influenced by the limited requirements for cold delivery in the vicinity of LNG terminals equipped with regasification technologies. Hence, this is a great challenge for the further development of LNG technology with regard to the outlook for future development of consumption.

3. Frameworks for advanced environmental evaluation of chemical processes

The physical reality can be described as the interconnection of three main spheres: biophysical, anthropological and technological. In this context, an anthropological activity consists of material and energetic flows moving from the biophysical sphere (namely the natural environment) to the anthropological one in order to sustain human needs. Afterwards, these flows return back to the biosphere as wastes.
In order to move towards sustainability, it is required to investigate and improve the technological sphere. In this regard, it is required to introduce the concept of *energy service*, namely the amount of energy required by the end-user as *useful energy*, i.e., the energy to support human life.
In particular, the stages of the energy trajectory can be briefly described as: (i) *primary energy* (the resources extracted from the biosphere: ground, sun, air, water bodies), which after a first transformation, is converted into an (ii) *energy carrier* in order to be transported or to be saved in different storage units, until finally distributed to consumers as (iii) *useful energy* to cover *energy services*. Each of these transformations require an energy expense. As mentioned, useful energy is the energy surplus able to cover energy services (after expenses are subtracted) and it depends on the chosen technology. The concept of *energy sustainability* has been described as the intersection of three fundamental and interlinked criteria (Fig. 3.1)[51]:

- *Proximity.* It concerns the location of the energy resource, namely the distance between the resource and the energy demand at the point of use. A sustainable energetic system should use the resources which are proximate in their geographical area.
- *Adequacy.* This criterion concerns not only the quality of the energy carrier with respect to the required energy service (heat, electricity, chemical) at the point of use, but also its origin or provenance (e.g., directly produced from a primary energy resource, surplus production or recovered after the first use).
- *Vitality.* The ability of a given technology to yield back to society *useful energy* besides sustaining its energy expenses. Hence the quantity of useful energy that the energy technology chain (ETC) reverses into society must surpass the energetic necessities of the ETC itself.

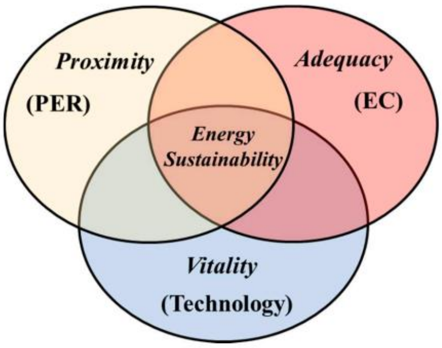

Figure 3.1: Venn diagram of New Energy Sustainability Paradigm. Figure taken from [51] with modifications

Since nowadays several technologies are available for covering similar energy services, tools for selecting the most appropriate one are required. Life cycle assessments (LCAs) and energy sustainability analysis (ESA) are the best candidates for this purpose, as they aim to measure the sustainability level of a technology both from an energetic and environmental point of view.

3.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is one of the three methodologies, namely life cycle costing (LCC), life cycle assessment (LCA) and social life cycle assessment (sLCA), which is part of the life cycle thinking (LCT). Therefore, LCT is the reflection of the concept of sustainability that is referred not only to the environmental sphere, but also extended to the economic and social ones. LCT aims to assess the burden of products/sectors/projects, adopting a holistic perspective, from raw material extraction to end of life scenarios.

In particular, LCA is a standardized (ISO 14040-44) and quantitative tool to assess the environmental impacts (i.e., the result of human activities on the five geo-components, namely lithosphere, hydrosphere, cryosphere, biosphere, and atmosphere, through a release or a consumption of resources) and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to end-of-life management (*cradle-to-grave* approach). Hence, LCA identifies and quantifies the used energy and materials, as well as flows released to the environment, and their potential impacts throughout the whole life cycle providing insights into the environmental sustainability of product/service systems.

Certain advantages and disadvantages of LCA are summarized in Table 3.1.

Table 3.1. Advantages and disadvantages of LCA.

Advantages	Disadvantages
- Evaluation of the complexity of the product, process or service aimed to underline the bottlenecks and to set the priorities of the interventions - System perspectives: improvements of the existing products and services - Evaluation and comparison of different alternatives - Analytical tool: it has an order structure to quantify the impact - Support of environmental policies	- To prove the sustainability it must be combined to economic and social studies (LCC and sLCA) - Static analysis - Data availability and quality: the goodness of the final result depends on the goodness of the input data - Geo-localized and time-referred - No absolute answer, since LCA is a tool of support

LCA can be performed both in the public and private sectors, and it can play a fundamental role in *eco-design* implementations. Eco-design is the process by means processes and products are designed with the aim to minimize the environmental impact during their whole life cycle.
The LCA framework is based on the construction of a model in which each phase of the life cycle is represented by *Unit Processes* inter-connected by flows of product, energy and materials.
Each *Unit Processes* relates to the eco-system from which it gets the natural resources and in which it releases wastes.
In order to perform LCA, four main steps have to be accomplished:

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Results interpretation

The goal and scope definition is the clear statement of the aims and targets of the LCA study. Once it is clear, the functional unit (FU) can be defined. The FU is a reference parameter to which ascribe the results of the LCA. The choice is arbitrary but should be consistent with the objectives of the study and with the function to which the product system was designed for.
Moreover, in this first step, it is mandatory to define the boundary conditions of the system: from *cradle to gate* (intermediate step of the analyzed chain) or from *cradle to grave* (end of life).
Data categories and data quality requirements are also fundamental, and they must be consistent with objectives and the field of application of LCA. For example, they can be primary data (detected/measured directly on site) or secondary data (coming from literature and databases).
Finally, cut off criteria for input and output must be defined: the product system should be modelled in such a manner that all the inputs and outputs at its boundary are elemental flows.
The second step of LCA is the life cycle inventory (LCI), whose aim is to provide a detailed description and quantification of the inputs of raw materials and fuels for a given product system (over its life cycle), and the outputs of byproducts and wastes (solid, liquid and gaseous). It is a systematic compilation of all physical exchanges between the product system and the environment, and it is characterized by: flow charts, data collection, allocation criteria and end of life management.
In particular, allocation is used for partitioning the inputs and outputs of a product, and it is necessary for processes that produce multiple products or co-products. Indeed, in many processes, more than one product is produced, and, in such cases, it is necessary to divide the environmental impacts from the process between the several products.

Two types of allocation can be performed: physic and economic. The former, attempts to divide the environmental impacts between products, as a function a quantitative measure (e.g., mass). The latter, on the other hand, distributes the impacts according to their economic value.
Therefore, through the LCI, a physical estimation of the impacts generated by a human activity is obtained. Nevertheless, both the consumption of resources and the waste emissions, influence the environment, generating a variation of its *status quo*. In this regard, the LCIA aims at assessing the magnitude and significance of the potential environmental impacts of a product/service system.
In particular, data obtained from the LCI (input and output flows such as resources consumption and emissions into air, water, soil) are assigned to the so-called *impact categories*, according to their ability of contributing to different environmental issues. Examples of *impact categories* are: global warming potential (GWP), ozone depletion, acidification, eutrophication, photochemical smog, among others. Following this first classification, the impact of each emission or resource consumption, is quantitatively modeled, according to the environmental mechanism, by employing a *characterization factor*. The latter is needed for expressing an inlet/outlet flow in the unit of the *impact category* which is referred to. For instance, GHG emissions are expressed as kg of CO_2 equivalent, and contribute to the *impact category* "climate change", leading to a temperature increase.
The one that was just described, is the LCIA conducted at the *midpoint* level. Nevertheless, the analysis can be extended to the *endpoint* level that, using different *characterization factors*, provides the *damage* associated to the impacts (i.e., an effective and quasi-permanent change of a system as a consequence of an anthropogenic activity).
The so-called *Areas of Protection* (AoPs) are the contexts in which the *damage* generated by an impact is qualitatively and quantitatively assessed. AoPs include: human health, ecosystem and natural resources. By way of example, GHG emissions condition the climate change generating a temperature increase, which affects the ecosystem.
The last step of LCA is results interpretation, in which the findings of either the inventory stage or the impact assessment is combined consistently with the defined goal and scope in order to reach final conclusions and recommendations.
Apart from conclusions and recommendations, consistency and completeness check, contribution, sensitivity and uncertainty analysis can/shall be performed.

3.2 Energy sustainability analysis (ESA)

The energy sustainability analysis (ESA) is a methodology which considers the entire energy trajectory from the energy source to the *useful energy* that, as mentioned, is used as a criterion for comparing the performance of different energy-producing technologies.
Hence, as it occurs in the LCA, also in this kind of analysis, the selection of appropriate boundary conditions is fundamental. In particular, the reference dimension of this analysis is the anthropologic sphere.
A viable technology (or an energy sustainable technology) should be able to produce an energy surplus (useful energy) which is able to feed society after the direct and indirect energy costs of the process itself are discounted. To better understand the concept of this analysis, some useful definitions are following:

- *Primary energy*. It is the energy embodied in a primary resource, namely a resource directly extracted from the natural environment (i.e., crude oil, sun…). Hence this energy, extracted from the biophysics sphere, is "for free". Nevertheless, in order to be utilized, it must be converted into an adequate *energy carrier* (i.e., solar energy, namely a primary energy, in order to be exploited, has to be converted into electricity which in this case is the *energy carrier*. For performing this conversion, an energy expense is required, due to the inefficiencies of the technology employed for the conversion itself).

- *Produced energy*. It is the accessible energy, namely the maximum obtainable energy by a process (a fraction of the available one), considering the thermodynamic efficiency limit of the process used depending on the operative conditions.
- *Direct energy*. It is the energy expense of a process in terms of electricity and heat consumption.
- *Indirect energy*. It includes all the additional energy requirements of the technology. Namely, it is the share of diverted energy from society, at anthroposphere level, to provide the materials, chemicals and fuels flows as well as other additional auxiliary services. It is the sum of several contributions which are summarized in Table 3.2.
- *Embedded energy*. It is the total energy spent for obtaining a product, including energy carriers. It can be expressed as *Cumulative Energy Demand* (CED) or as *Gross Energy Demand* (GER). The former, differently from the latter, takes into account also the energy content of the carrier. Therefore, the CED is the total energy expenditure subtracted by both the anthropological sphere and the biophysics one (including both the renewable and non-renewable resources). On the contrary, the GER is the summation of the energy carriers spent to obtain a product. Hence, it depends on the energy expenditures at the anthropological level, which are function of the state of the art of the technology. As mentioned, it does not consider the energy contained in the energy carrier.

Table 3.2: Indirect energy contributions [52].

$E_{ind,i}$	Description
E_{chem}	Indirect energy used to produce the chemicals of the process
E_{mat}	Indirect energy used to produce the materials of the process
$E_{ind\ to\ produce\ Edir}$	Indirect energy used to produce and use the direct energy of the process
E_{maint}	Indirect energy used for maintenance purposes
E_{labor}	Indirect energy used to sustain the human labor
E_{constr}	Indirect energy used for construction purposes
E_{decomm}	Indirect energy used for decommissioning purposes
E_{amort}	Indirect energy allocated for the amortization of materials and chemicals of the replacement facility

In order to perform the energy analysis, CED values are used to transform the materials and chemicals flows into energy equivalents at the technological boundary [52]:

$$E_{chem} = \sum_{i=1}^{n} \left(CED_i \cdot m_{chem,i} \right) \tag{3.1}$$

$$E_{mat} = \sum_{i=1}^{n} \left(CED_i \cdot m_{mat,i} \right) \tag{3.2}$$

For the purposes of the sustainability analysis, which is aimed to be performed, an investigation of the E_{amort} term is mandatory. Indeed, this contribution is a key difference between LCA and ESA. Amortization is needed to account for the possibility of reproducing the technology under analysis (in energy terms). This concept is one of the main pillars of the sustainability concept itself: a technology, in order to be sustainable, has to be *vital*, namely reproducible to maintain the coverage of energy services in the anthropological sphere.

Therefore, an energy technology must be able to produce at least a quantity of energy both for sustaining its operational necessities and for its reproduction. The remaining part is the one able to feed civilization in an appropriate form (*useful energy*).. Moreover, as mentioned, this surplus increases if the *adequacy* and *proximity* concepts are respected as well. Namely, the resources used by an energetic system should be both as proximate as possible to its geographical area, and adequate to the specific energetic service to be covered.
As a summary, Figure 3.2 shows the energy trajectory from the primary energy to the useful one.

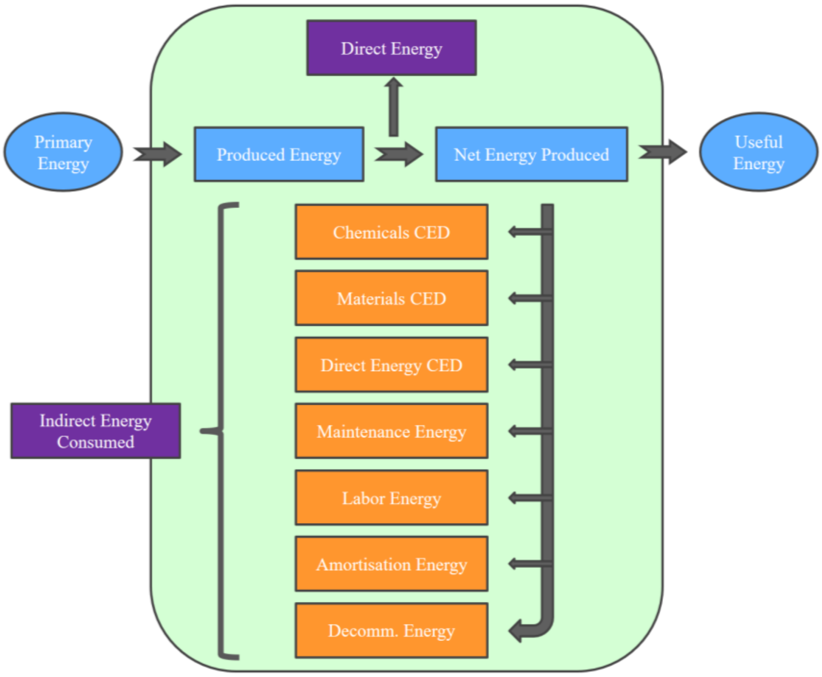

Figure 3.2: Energy trajectory from the primary energy to the useful one.

The ESA is conducted at two levels:

iii. Short-term: the energy sustainability index (ESI) is evaluated for establishing whether the produced energy is able to cover the direct energy expenses needed to run the technology,

iv. Long-term: energy return on investment (EROI) and energy payback time (EPT) indicators are evaluated for taking into account all the indirect energy quotas and the full life cycle energy expenses.

EPT indicates the time framework that a particular technology requires for the compensation of the indirect energy diverted for the production of materials and its construction along with other important energy investments.
On the other hand, EROI is a measure of energy profitability of energy sources and technologies. Indeed, it relates the amount of net energy produced (a derived flow resource within the technological boundary) to the total invested energy to score energy-producing processes. Different expressions for the EROI formula can be found in literature, therefore, it is mandatory to specify the one selected for the analysis conducted.
Equations 3.3-3.7 summarized the formulas employed for calculating the parameters discussed under the ESA framework.

$$E_{net} = E_{prod} - E_{dir} \tag{3.3}$$

$$E_{useful} = E_{net} - E_{ind} \tag{3.4}$$

$$ESI = \frac{E_{prod}}{E_{dir}} \tag{3.5}$$

$$EROI = \frac{E_{net}}{E_{ind}} \tag{3.6}$$

$$EPT = \frac{E_{ind}}{E_{net}/lifespan} \tag{3.7}$$

4. Case study: LCA and ESA applied to Coral Sul FLNG

Between 2011 and 2014, three NG offshore reservoirs amounting to 2.400 bcm, have been discovered in the Rovuma basin located in Mozambique. In order to exploit this massive resource, in November 2016, the Italian oil & gas company Eni authorized investments for the first phase of the *Coral South project*, namely the construction of a new FLNG facility: Coral Sul. The facility was designed for sustaining a productivity of 3.4 million tons per year (mtpa) of NG, for a lifespan of 25 years.

Differently from the other already operating FLNG projects (i.e., Petronas and Prelude), Coral claims to be developed with an energy-optimized approach based on a systematic analysis of efficiency. Indeed, specific techniques have been applied to minimize as much as possible the environmental impact (i.e., CO_2 emissions) and the energy demand, especially for the NG liquefaction, which, as mentioned, is among the most energy intensive operations in the FLNG chain.

As a result, Coral's nameplate energy consumption is significantly lower than the FLNG industry average today operating. Indeed, it has been declared an energy consumption of 256 kWh per ton of produced LNG, compared to the average range 275 - 400 kWh registered by other facilities [53] . While construction started in September 2018, the first shipment of LNG was reported to depart on the 13th November 2022.

The present thesis aims to perform the LCA and the ESA of FLNG facilities, examining as case-study the Coral Sul. The study includes both, insights into the upstream phase and into the full supply chain. These results have been compared, both from an energetic and environmental perspective, to the ones obtained for the conventional LNG and NG supply chains.

4.1 Coral Sul FLNG full supply chain

Coral Sul is a FLNG facility operating in the Rovuma basin (Mozambique). On this platform, the upstream operations of the NG supply chain (production and processing), liquefaction and storage of LNG are performed. As mentioned above, LNG carriers are employed for transporting the produced LNG to a pre-established receiving regasification terminal.

Regarding the transport phase, for the case analyzed in this thesis, a distance of 10.000 kilometers by LNG carrier was estimated, indicatively this choice represents the route from the Rovuma basin to the Panigaglia LNG terminal (Italy), where regasification is hypothesized to occur. For this purpose, a navigation simulator was employed, assuming an average speed for the LNG carrier of 15.9 knots, for which a navigation of about 20 days is required (Fig. 4.1).

Figure 4.1: Simulation of the LNG carrier route: from the Rovuma basin (MZ) to the Panigaglia receiving terminal (IT).

Once that LNG is regasified (i.e., transformed back into the gaseous form), 300 kilometers of pipelines were assumed for its national distribution, considering the average pipelines length of the Italian network [54].
A schematic of the FLNG supply chain and the boundaries considered for its LCA and ESA are shown in Fig. 4.2.

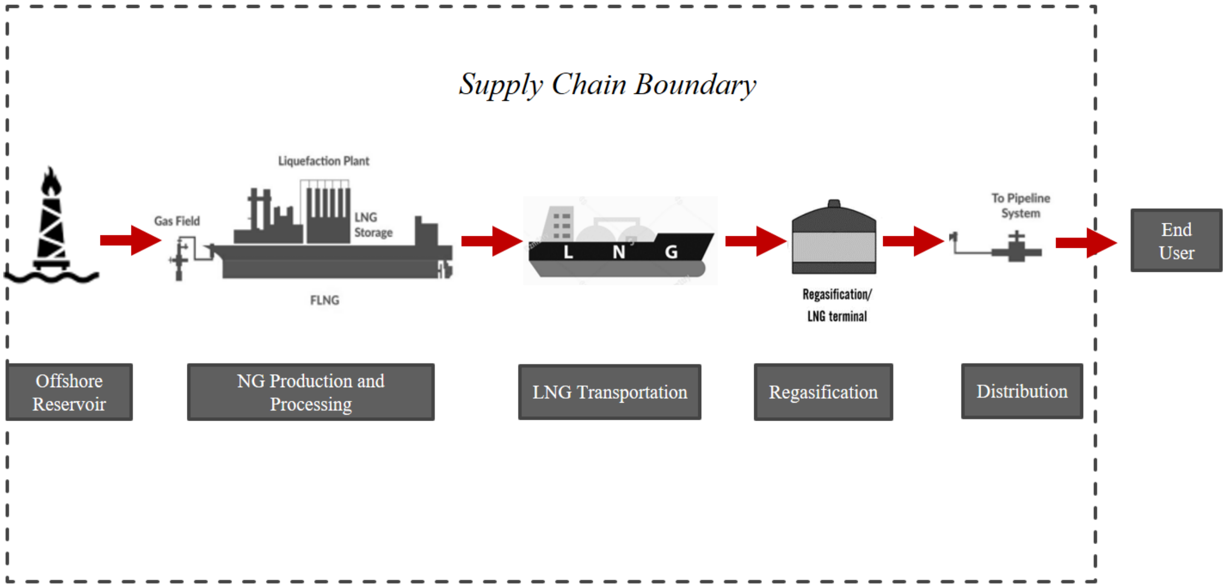

Figure 4.2: Schematic of the FLNG supply chain.

4.2 Scope definition

As mentioned, the first mandatory step of a sustainability analysis (both ESA and LCA) is the scope definition. The objective of the LCA in the present case is to evaluate the environmental footprint of the FLNG, through a detailed study of the unit operations, required equipment and key exchanges (inputs/outputs) with the biosphere/technosphere for its operation during its useful life. Apart from studying the production phase (and initial treatment of NG), it also seeks to compare the production chains for NG that use liquefied transport to the traditional transport method through gas pipelines. This last step also seeks to establish the conditions in which the FLNG could be competitive as an option for NG supply, based on the distance to be traveled and the environmental footprint in each case. Similarly, the ESA seeks to offer a perspective of energy sustainability to the NG supply chain, to determine if it can effectively supply society with useful energy (and in what proportion with respect to the investment), in addition to determine the energy payback time.

For these scopes, different boundaries are considered depending on the analysis carried out. For the first case, the FLNG and other LNG production processes are examined, hence the boundary includes extraction, treatment and liquefaction operations. For the full supply chain up to the end-user of the NG, the boundaries are extended to include transport, regasification and distribution operations. The functional unit for the analysis is 1 Sm^3 of natural gas.

4.3 Inventory analysis

The inventory analysis is a detailed description and quantification of raw materials and fuels inputs for a given product system (over its life cycle), and the outputs of solid, liquid and gaseous wastes.

Considering the scope of the thesis, inventory data was compiled for the FLNG platform. Different literature sources were used (comprehending primary and secondary data) which have been collected from different reports and available material. The data for the FLNG platform was then benchmarked against secondary averaged representative data that are present on Life cycle inventory (LCI) databases. Hence, for the LNG and NG production and processing processes (and their related supply chains), the data needed to perform ESA and LCA are taken from already available databases, which will be explored in more detail in the following paragraphs.

A typical FLNG facility configuration, which serve as main rationale for the construction of the inventory, is represented in Fig. 4.3.

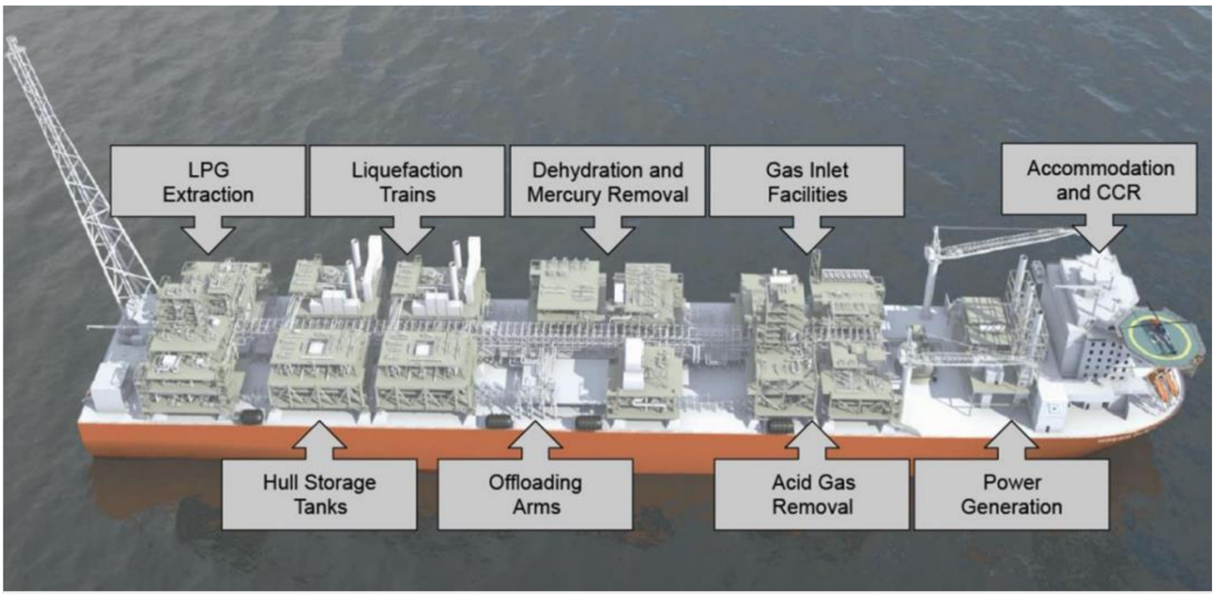

Figure 4.3: Typical FLNG facility configuration. Figure taken from [55] with modifications.

The first step for the inventory of Coral, is estimating the amount of the employed materials. Although aggregated quantities of required materials are declared by the constructers, there is limited information available about the specific materials and quantities used for each section. Here, it has been hypothesized duplex stainless steel and aluminum as the main construction materials. The use of one versus the other depends on the specific application.

Corrosion is a major issue for offshore structures and platforms, as they are exposed to a chloride-rich environment, wet-dry cycles, high humidity, and microbiological attacks. They may also be subjected to abrasion and wear from sand, floating waste and currents. Therefore, material selection plays a fundamental role for determining the reliability, maintenance needs and lifetime of offshore structures which, like Coral, are expected to stay in service 25 years in harsh marine corrosive environments.

Duplex stainless steel [56] is recognized as the ideal material for marine applications: it has an excellent corrosion resistance, high strength, high resistance to erosion and extended fatigue life [57]. On the other hand, aluminum is suitable for cryogenic applications (i.e. liquefaction). Aluminum 5083 [58] was selected due to its high strength, corrosion resistance and excellent performance in the harsh marine environment.

In order to perform a proper materials inventory analysis, the total amount (kilograms) of steel and aluminum must be calculated since they are the main construction materials. For this estimate, dimensions of each unit are required. For each unit, the amount of required material is estimated using basic design calculations, based on the declared flows of NG that are produced (and the consequent required equipment for those). These estimates were also counter-check and completed with primary data found on literature (summarized in Table 4.1).

Table 4.1: Material amount of some units and equipment of the FLNG platform, found on literature.

Unit	Material	Lifetime	Material amount [kg]	References	Comments
Hull	Steel	25	$1{,}4\cdot10^{8}$	[59]	This estimate takes into account also the storage tanks, which are 8 membrane-types tankers with a capacity of 29.839 m^3_{LNG} each.
Turret	Steel	25	$6{,}10\cdot10^{6}$	[60]	
Living quarters	Aluminum	25	$2{,}00\cdot10^{6}$	[61]	Considering that the floating facility is designed to host 350 workers on board, the material amount needed for the living quarter was estimated making a comparison with similar structures found on literature.
Cryogenic exchangers	Aluminum	25	$4{,}89\cdot10^{6}$	[62]	
Refrigeration MR2 train B (Unit S02)	Aluminum	25	$3{,}04\cdot10^{6}$	[62]	
Refrigeration MR1 train B	Aluminum	25	$4{,}00\cdot10^{6}$	[62]	

and ITR2 (Unit S04)					
Turbine GTG (PGT25+G4)	Steel	15	$1{,}23 \cdot 10^5$	[63]	The kilograms estimated are referred to the four turbines employed in the FLNG facility.
Mooring system	Steel	25	$9{,}00 \cdot 10^6$	[64]	

As mentioned above, apart from what is listed in Tab. 4.1, estimates must be done for certain units and equipment installed on the FLNG under study for the inventory compilation based on the general layout of this type of platforms. Reference dimensions for each unit required for processing raw reservoirs fluids (Fig. 4.3) are estimated based on the declared production and specification of the reservoirs fluids. Hence, using basic design equations, diameters, heights and consequentially volumes and weights, were estimated. In order to simplify the approach, columns, vessels, heat exchangers, pumps and compressors, were generally assumed as cylindrical shells with spherical bottoms.
For performing this estimation and calculating the thickness of each equipment, a basic design equation (following the regulation of *EN 13445 – Unfired pressure vessel*) was employed (4.1):

$$e = \frac{P \cdot Di}{2 \cdot f \cdot z - P} \tag{4.1}$$

In this equation, P is the pressure which the equipment is subjected to (these values were taken from similar units), D_i is the internal diameter, z is the *testing group* (hypothesized equal to 1) and f is the maximum allowed value of the nominal design stress. The latter is calculated following Eq. 4.2:

$$f = \min\left(\frac{R_{p0,2/t}}{1{,}5}; \frac{R_{m/20}}{2{,}4}\right) \tag{4.2}$$

The $R_{p0,2/t}$ and $R_{m/20}$ values were found on the data sheets of the specific steel [56] and aluminum [58] chosen for the inventory phase. Moreover, due to the harsh marine environment, a corrosion allowance of 0,012 meters was considered and summed to the main thickness values calculated with Eq. 4.1. Once that the volume of the equipment was calculated, using Eq. 4.1-4.2 for the thickness and the basic formula for cylindrical and spherical geometries (Eq. 4.3 - 4.4, respectively), the associated kilograms can be easily obtained by multiplying the cubic meters of the volume by the density of the specific material.

$$V_c = \pi \cdot ({r_1}^2 - {r_2}^2) \cdot h \tag{4.3}$$

$$V_s = \frac{4}{3} \cdot \pi \cdot ({r_1}^3 - {r_2}^3) \tag{4.4}$$

Furthermore, since the aim of the thesis regards the whole lifetime of the facility (and of each equipment), the additional materials needed along the lifespan of the facility (i.e., 25 years) for maintenance or substitution were also considered.
The first analyzed unit is the acid gas removal unit (AGRU). The purpose of the unit is removing acid gases (i.e., H_2S and CO_2) in the feed gas coming from the inlet facilities. Their removal is mandatory for preventing freezing and other issues in the downstream cryogenic units and to meet sales specifications. The AGRU can be divided into four main sections: initial phase separation, absorption and flash, regeneration and amine recovery. The initial phase separation

aims to remove MEG (namely mono-ethylene-glycol injected at the wellhead and at the gas receiving facilities as corrosion and hydrates inhibitor) and water and liquid hydrocarbons entrainments. Then, a packed column works as an absorber in which the amine solution flows countercurrent, working as liquid desiccant for removing acid gases. The saturated amine solution is regenerated and recovered thanks to the presence of specific heat exchangers, which allow to reach the temperatures needed for the desorption phase. The values for the inventory for each equipment of this unit are summarized in Table 4.2.

Table 4.2: Material amount of the equipment composing the AGRU.

Unit	Pressure [MPa]	Diameter [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]
Acid gas absorber	8,5	8,46	24,4	1	131,02	15	Steel	$1{,}73\cdot10^6$
Washing tower	8,5	6,58	19,74	1	64,99	15	Steel	$8{,}56\cdot10^5$
Sweet gas KO drum	8,5	6,016	18,8	1	51,72	12	Steel	$8{,}51\cdot10^5$
Feed gas water cooler	5,5	9,4	17,7	1	132,49	7	Steel	$3{,}74\cdot10^6$
Amine regenerator	3,5	9,231	20,272	1	62,23	20	Steel	$6{,}15\cdot10^5$
Amine regenerator condenser	3,5	12,67	20,272	1	125,00	15	Steel	$1{,}65\cdot10^6$
Rich amine flash drum	3,5	8,869	20,272	1	57,13	5	Steel	$2{,}26\cdot10^6$
Amine regenerator reboiler	3,5	9,05	26,245	1	71,77	10	Steel	$1{,}42\cdot10^6$
MEG injection pumps	8,5	8,145	22,625	1	99,33	15	Steel	$1{,}31\cdot10^6$

The second estimated unit is the dehydration and then the mercury removal one. Water is removed to avoid freezing and hydrates formation, whereas mercury is removed to avoid its adverse effects in downstream cryogenic units. The dehydration unit is assumed to be composed of three main sections: separation, adsorption and filtration, and regeneration. A knockout (KO) drum is first used for removing and accumulating condensed and entrained liquids from the feed gas coming from the AGRU. In order to remove water and amine, tree molecular sieves gas driers are employed. Finally, for the regeneration phase, heat exchangers are used for reaching the required temperature (about 230 °C). The specifications indicate that the dry gas at the molecular sieve gas driers outlet shall contain a maximum of saturated water of 0.5 ppm. The mercury removal unit is used for removing mercury in the dried gas stream by the active sulfur in the adsorbent phase. A single non-regenerable bed is assumed for this operation. The gas at the adsorber outlet shall contain less than 0.01 µg/sm$^3_{NG}$ of mercury content. The values of materials amount estimates for each equipment of these units are summarized in Table 4.3.

Table 4.3: Material amount of the equipment composing the dehydration and mercury removal unit.

Unit	Pressure [MPa]	Diameter [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]
Molecular sieve dehydration unit	8,5	3,4	6,334	3	21,18	10	Steel	$4,18 \cdot 10^5$
Mercury removal unit	8,5	7,9	24,44	1	53,67	5	Steel	$2,12 \cdot 10^6$
Fuel gas mixing drum	5,68	11,26	18,8	1	70,93	10	Steel	$1,40 \cdot 10^6$
Regeneration gas KO drum	5,68	13,16	20,68	1	93,23	12	Steel	$1,53 \cdot 10^6$
Regeneration gas air cooler	5,68	9,4	26,32	1	70,42	12	Steel	$9,27 \cdot 10^5$
Superheater	8,5	11,28	13,16	1	100,24	25	Steel	$7,92 \cdot 10^5$
Sweet gas cooler	8,5	8,46	24,44	1	114,68	25	Steel	$9,06 \cdot 10^5$

The gas exiting from the mercury removal unit then is sent to the natural gas liquids (NGL) recovery and fractionation units. The purpose of this unit is to remove the C_{5+} and benzene from the dry sweet feed gas, and to partially extract ethane and butane required for refrigerant make-up in the NG liquefaction unit which will follow. The final product of this section is a lean gas, which is free from heavy components, which is able to be fed to the liquefaction section. The NGL recovery occurs via cryogenic distillation, for this, brazed aluminum heat exchangers (BAHX) are required to cool the process fluids down. These are placed inside cold boxes that combine BAHX with the required type of complementary cryogenic equipment, such as KO drums, injection drums, valves, instrumentation.

The fractionation unit is composed of four main equipment, namely four packed columns performing the separation of the different hydrocarbons from the main gas stream: demethanizer, debuthanizer, deethanizer, depropanizer. Ethane and butane have a fundamental function inside the facility under study: they both work as refrigerants (only propane is not used for this purpose) in the liquefaction unit and as fuel gas for providing the required direct energy. The values of material amount found for each equipment of these units are summarized in Table 4.4.

Table 4.4: Material amount of the equipment composing the NGL recovery and fractionation unit.

Unit	Pressure [MPa]	Diameter [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]

NGL reinjection drum	2,1	10,68	23,53	1	61,85	5	Steel	$2,44\cdot10^{6}$
Deethanizer column	1,9	9,05	47,97	1	71,46	10	Steel	$1,41\cdot10^{6}$
Depropanizer column	1,65	9,05	47,97	1	64,57	10	Steel	$1,28\cdot10^{6}$
Debutanizer column	2,1	7,24	37,11	1	40,77	10	Steel	$8,05\cdot10^{5}$
Demethanizer column	8,5	5,792	47,06	1	102,30	10	Steel	$2,02\cdot10^{6}$
Low temperature separator	8,5	9,05	15,39	1	111,10	15	Steel	$1,46\cdot10^{6}$
Feed gas compander	8,5	9,05	16,29	1	84,35	10	Steel	$1,67\cdot10^{6}$
Demethanizer cold box	8,5	6,335	15,385	1	42,02	25	Aluminum	$1,12\cdot10^{5}$
End flash drum	8,5	7,24	14,48	1	53,92	25	Aluminum	$1,43\cdot10^{5}$
Compressor aftercooler	8,5	8,145	12,67	1	62,59	25	Aluminum	$1,66\cdot10^{5}$
Booster compressor	8,5	6,335	13,575	1	38,69	25	Aluminum	$1,03\cdot10^{5}$
LNG liquid Turbine	8,5	8,869	19,005	1	102,87	25	Aluminum	$2,47\cdot10^{5}$

The last step is the liquefaction, and it serves to pre-cool, liquefy and sub-cool the NG stream coming from the NGL fractionation. The chosen technology for liquefaction is the dual mixed refrigerant (DMR). This liquefaction approach consists of two hydrocarbons-based refrigerant cycles: the refrigeration cycle for pre-cooling (Warm Mixed Refrigerant or MR1) and the refrigeration cycle for liquefaction/sub-cooling (Cold Mixed Refrigerant or MR2). Pre-cooling and liquefaction/sub-cooling are performed in the Warm Main Cryogenic Heat Exchanger (MCHE) and Cold MCHE, which are both Spiral Wound heat exchangers, respectively.
Some equipment of this unit have been estimated as previously explained (Table 4.5), but for others (i.e., cryogenic exchangers, refrigeration MR1 and MR2) values were found in literature and they already summarized in Table 4.1.

Table 4.5: Material amount of the equipment composing the NG liquefaction unit.

Unit	Pressure [MPa]	Diameter [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]
Heating medium exp. Drum	8,5	12,22	18,8	1	252,01	25	Steel	$1,99\cdot10^{6}$

Ethane vaporizer	8,5	9,4	15,04	1	119,56	25	Aluminum	$3{,}18\cdot10^5$

The main electrical power generation of the FLNG platform under study is provided by four gas turbine generators (GTG), whereas two essential diesel generators allow full functionality of systems related to life on board, start of one main generator and emergency situations (e.g., crew safety, possible floater evacuation). The formers are characterized by an installed power of 30-35 MW each (hence a total of 120-140 MW installed power). On the other hand, the diesel generators have a power of 6 MW each (for a total of 12 MW of installed power). The GTGs are fed with the produced fuel gas (a cut containing butane, propane and ethane) the NGL recovery and fractionation units.

It is important to note that neither GTGs nor diesel generators work at their full capacities. It was found in the reports that c. 256 kWh are needed for each ton of produced LNG. Moreover, considering the purpose for which they have been designed, for the 12 MW of the diesel generators, a utilization frequency (at their full capacity) of one day a week was considered.

Regarding the thermal utilities requirements, they are covered by using sea water and hot oil. Sea water is used in this type of platforms as the main cooling medium since due to the thermal duties to be released from the process facilities air cooling would be impractical. Sea water is taken at about 150 meters depth by specific risers: water from this depth is colder than the surface one, hence energy requirements for cooling are reduced. After its utilization, this water is returned back to the sea at an average temperature of 30,6 °C, complying with the main regulations. Hot oil is selected as heating medium, in a close loop arrangement with the Waste Heat Recovery Unit (WHRU) on GTGs. The main required equipment for providing utilities and power generation are summarized in Table 4.1 and 4.6, where the calculation for the material amount was performed similarly to the previous units.

Table 4.6: Material amount of the equipment composing the power generation and utility unit.

Unit	Pressure [MPa]	Diameter [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]
Waste heat recovery unit	8,5	17,86	24,44	1	572,10	25	Steel	$4{,}52\cdot10^6$
IA receiver	8,5	8,46	28,2	1	180,27	25	Steel	$1{,}42\cdot10^6$

The offloading unit is mainly composed of loading arms, which allow to transfer LNG from one tank to another through an articulated pipe system. Therefore, these arms were estimated as cylindrical shells, employing the same thickness formula of the previous units analyzed. No bottoms are assumed present in this case. Results are summarized in Table 4.7.

Table 4.7: Material amount of the equipment composing the offloading unit.

Unit	Pressure [MPa]	Diameter [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]
LNG loading arm	8,5	5,8	23,53	3	174,31	25	Aluminum	$4{,}64\cdot10^5$
LNG loading and	8,5	8,14	47,97	1	110,73	25	Aluminum	$2{,}95\cdot10^5$

BOG return arm			

Due to its massive dimensions, the gas flare heavily contributes to the total amount of steel employed for the platform, constituting about the 7,8% of it (Table 4.8). The gas flare is a vertical structure, whose main function is burning off flammable streams released by pressure relief valves during unplanned over-pressuring of plant equipment. Hence, its purpose is that of safety by protecting pressure vessels or pipes from unplanned operational upsets. For dimensioning its prismatic structure, an average side was considered for calculating a parallelepiped shell with a square base (again, thickness is estimated using Eq.4.1-4.2).

Table 4.8: Material amount for the gas flare.

Unit	External side [m]	Internal side [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]
Gas flare	16	15,6	175	1	2212	25	Steel	$1{,}75 \cdot 10^7$

Several instrumental technical rooms (ITR) must be present on FLNG platforms. Their structure was estimated as an aluminum parallelepiped shell, whose thickness has been calculated following Eq. 4.1-4.2. Table 4.9 summarizes the results.

Table 4.9: Material amount for ITRs.

Unit	External side [m]	Internal side [m]	Height [m]	No. of equipment per unit	Total volume [m^3]	Lifetime [years]	Material	Material amount [kg]
ITR1	15,04	14,64	21,62	1	347,15	25	Aluminum	$9{,}23 \cdot 10^5$
ITR2	11,765	23,53	11,36	1	273,06	25	Aluminum	$7{,}26 \cdot 10^5$

For the extraction of the raw reservoir fluids, six production wells are employed. Each of them is composed of three main steel-made items: the Christmas tree, the riser and the casing. Hence, in Table 4.10 each value related to the specific item has been multiplied by a factor of 6. Following literature data, each riser, considering a sea depth of about 2000 meters (depth at which the floating facility operates), weighs approximately 1700 tons [65]. For the same depth each tree weights 70 tons, according to literature [66]. Finally, casing dimension of 20" were considered following [67], and a weight of c. 594 tons was estimated.

Table 4.10: Material amount for the NG production system.

Unit	Material	Material amount [kg]
Risers	Steel	$1{,}02 \cdot 10^7$
Christmas tree	Steel	$4{,}20 \cdot 10^5$
Casing (20")	Steel	$3{,}56 \cdot 10^6$

As a summary, Table 4.11 indicates the total amount of estimated steel and aluminum required by the analyzed FLNG platform along its lifespan of 25 years, and the kilograms of material

needed for producing 1 standard cubic meter (Sm^3) of NG (i.e., materials were prorated to the total expected production). Therefore, for obtaining the last column of Tab 4.11, the total aggregated amount of each term was prorated to the total expected NG produced by the platform along its lifecycle, namely $1{,}16 \cdot 10^{11}$ Sm^3_{NG} (taking into account the nameplate capacity of 3,4 mtpa of LNG, for which a density of 0,735 kg/m^3 was considered).
The inventory phase resulted in an aggregated estimated quantity of 246.000 tons for FLNG platform. This result is about 11% higher than the values reported by operators of the platform (Eni) as total weight of the structure (which is around 220.000 tons). This 11% higher includes additional materials flows which have been estimated here for supporting the facility along its lifespan (e.g., including operations such as commissioning, decommissioning, and maintenance, among other).

Table 4.11: Material amount for the analyzed FLNG platform along its lifetime.

Material	Total amount [kg]	$kg_{material}/Sm^3_{NG}$
Steel	$2{,}23 \cdot 10^{8}$	$1{,}92 \cdot 10^{-3}$
Aluminum	$2{,}31 \cdot 10^{7}$	$1{,}99 \cdot 10^{-4}$
Total	$2{,}46 \cdot 10^{8}$	$2{,}12 \cdot 10^{-3}$

As initially mentioned, the inventory analysis should include the key technosphere and biosphere exchange flows. [68] performed an environmental impact assessment for the FLNG platform, and reported liquid and solid input/output flows, atmospheric emissions and utilities, which are summarized in Table 4.12-4.14. In particular, Table 4.12 shows the estimated chemicals flows which will be required. Also in this case, the amount indicated for each term reflects the projected volumes along the lifetime.

Table 4.12: Chemicals amount for the FLNG platform.

Chemical	Total amount [kg]	$kg_{chemical}/Sm^3_{NG}$	Notes
Molecular sieve	$9{,}05 \cdot 10^{5}$	$7{,}80 \cdot 10^{-6}$	Axsorb 533 (alumina) and Axsorb 510 (zeolite) are used as dehydration adsorbants
Mercury adsorbant	$1{,}34 \cdot 10^{5}$	$1{,}16 \cdot 10^{-6}$	Axtrap 273 adsorbent (alumina) is used as adsorbant for the mercury removal
Amine carbon bed	$1{,}50 \cdot 10^{5}$	$1{,}29 \cdot 10^{-6}$	
MEG	$1{,}80 \cdot 10^{8}$	$1{,}55 \cdot 10^{-3}$	
MDEA	$1{,}56 \cdot 10^{8}$	$1{,}34 \cdot 10^{-3}$	
Oil and lubricants	$1{,}19 \cdot 10^{5}$	$9{,}77 \cdot 10^{-7}$	
Inert activated alumina ceramic balls	$1{,}20 \cdot 10^{5}$	$1{,}03 \cdot 10^{-6}$	Used both in the molecular sieve and in the mercury removal column together with Axsorb 533/510 and Axtrap 273 respectively.

Table 4.13 shows the utilities needed for satisfying both the electrical demand and the thermal requirements. On the other hand, in Table 4.14 the atmospheric emissions are listed.

Table 4.13: Utilities amount needed by FLNG platform.

Utility	Total amount [kg]	$kg_{utility}/Sm^3_{NG}$	Notes
Fuel Gas	$4{,}13\cdot10^{9}$	$3{,}56\cdot10^{-2}$	An efficiency for the electrical energy production of 0,41 has been considered. Note that, as mentioned, the fuel gas is produced on the platform itself.
Diesel	$3{,}29\cdot10^{7}$	$2{,}84\cdot10^{-4}$	
Cooling water (sea water)	$6{,}02\cdot10^{12}$	$5{,}19\cdot10^{1}$	
Hot oil	NA	NA	

Table 4.14: Atmospheric emissions generated by the FLNG facility.

Atmospheric emission	Total amount [kg]	$kg_{emission}/Sm^3_{NG}$	Notes
NO_x	$4{,}82\cdot10^{7}$	$4{,}16\cdot10^{-4}$	
SO_x	$6{,}96\cdot10^{4}$	$6{,}00\cdot10^{-7}$	
CO	$2{,}44\cdot10^{6}$	$2{,}10\cdot10^{-5}$	
CO_2	$4{,}03\cdot10^{9}$	$3{,}47\cdot10^{-2}$	
Particulate matter (PM)	$1{,}04\cdot10^{5}$	$9{,}00\cdot10^{-7}$	
Non-methane volatile organic compound	$3{,}13\cdot10^{5}$	$2{,}70\cdot10^{-6}$	
Ethane	$3{,}65\cdot10^{5}$	$3{,}15\cdot10^{-6}$	Term that accounts for refrigerant losses
Butane	$5{,}10\cdot10^{5}$	$4{,}40\cdot10^{-6}$	Term that accounts for refrigerant losses
Methane	$1{,}06\cdot10^{9}$	$9{,}12\cdot10^{-3}$	It represents the fugitive emissions of methane (over facility lifespan) amounting to the 1% of the NG extracted
Biological Oxygen Demand (BOD5)	$1{,}75\cdot10^{5}$	$1{,}51\cdot10^{-6}$	
Oils	$6{,}79\cdot10^{4}$	$5{,}87\cdot10^{-7}$	
Total suspended solids (TSS)	$2{,}56\cdot10^{5}$	$2{,}21\cdot10^{-6}$	
Mercury	$5{,}80\cdot10^{-1}$	$5{,}00\cdot10^{-12}$	

After this inventory phase, all collected data will be used for performing the successive phases of the LCA and the ESA of Coral Sul, as they will be reported in the following chapters.

4.4 Results

The first scope of the analysis is to investigate the production and processing phases performed by the FLNG platform. For this, two different scenarios were taken into account. The first one considered production at its nameplate capacity, without any shut-downs due to factors such as maintenance, technical or security problems, among others (as the maximum theoretical potential). In this case, a constant production of 3,4 mtpa of LNG for 25 years is considered. The second scenario, a more realistic one, took into account the so-called *Activity Level* of the facility (Fig. 4.4), a parameter which is used in this type of plants.

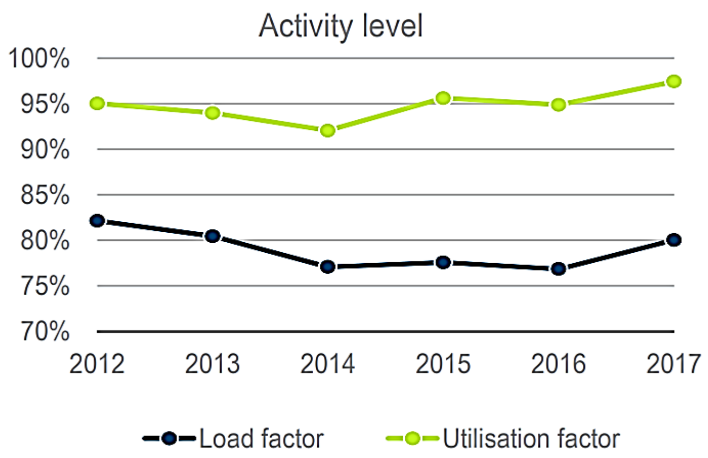

Figure 4.4: Activity Level trends of LNG plants from 2012 to 2017. Figure taken from [18] with modifications.

The *Activity Level* of a LNG plant is influenced by two factors:

- *Load factor*: it is the ratio of the actual output in a given year against the nameplate capacity.
- *Utilization factor*: it is the ratio of the actual output to potential maximum output (it takes into account both planned and unplanned outages).

Therefore, considering the average values of these two terms showed in Fig. 4.4, and in order to carry out a conservative analysis, a value of 0,8 and 0,9 were chosen for the *Load Factor* and the *Utilization Factor*, respectively. Overall, hence, an *Activity Level* of 70% was selected as realistic scenario of the FLNG platform.
As mentioned in the scope section 4.2, this thesis aimed to investigate also the full supply chain, besides merely the production phase. Moreover, the platform under study was benchmarked against other alternative production processes of NG and their respective supply chains. These are the "conventional" LNG and NG ones. The results include then a comparison among different NG transport option, in order to highlight advantages and drawbacks of each of them.

4.4.1 Impact assessment

The evaluation of the FLNG platform from an environmental perspective was one of the main goal of the thesis. In the first instance, the steps from extraction to liquefaction were considered. Afterwards, the evaluation of the entire supply chain was carried out. Since NG mainly serves to cover different societal energy services, 1 Sm^3 of NG produced was chosen as functional unit (FU) of the LCA. As mentioned above, the datasets were obtained from *Ecoinvent v3.9* cutoff database, using the *Activity-Browser* software.
In particular, for the impact assessment, the CED and CML v4.8 2016 methods were used. The CML v4.8 2016 method includes the following impact categories [69]:

- *Acidification* [kg SO_2 equivalent]: When acidic gases, such as sulphur dioxide, react with water in the atmosphere, "acid rains" may form and lead to an increase of acidity in water and soil systems. Therefore, this category can be defined as the reduction of the pH due to the acidifying effects of anthropogenic emissions.
- *Climate change (GWP100)* [kg CO_2 equivalent]. It is the change in global temperature caused by the greenhouse effect that the release of greenhouse gases by human activity creates. It is expressed as Global Warming Potential over the time horizon of different years, being the most common 100 years (GWP100).
- *Depletion of abiotic resources* [MJ of fossil fuels, kg Sb equivalent]. It is referred to the consumption of non-biological resources such as fossil fuels, minerals, metals and water, among others. This category reflects the decrease of the availability of these resources as a result of their unsustainable use.
- *Ecotoxicity* [kg 1,4-DB equivalent]. Environmental toxicity is measured as three separate impact categories which examine freshwater, marine and land. It accounts for the emissions of some substances, which can have impact on an ecosystem such as biodiversity loss and/or extinction of species.
- *Eutrophication* [kg PO_4^{3-} equivalent]. It refers to the accumulation of chemical nutrients in aquatic systems. This causes excessive plant growth like algae in rivers which causes severe reductions in water quality and animal populations. Emissions of ammonia, nitrates, nitrogen oxides and phosphorous to air or water all have an impact on eutrophication.
- *Human toxicity* [kg 1,4-DB equivalent]. It represents the toxic effects of chemicals on humans. In particular, it is a calculated index which reflects the potential harm of a unit of chemical released into the environment, and it is based on both inherent toxicity of a compound and its potential dose. These chemicals emissions can lead to cancer, respiratory diseases, among others.
- *Ozone layer depletion* [kg CFC-11 equivalent]. It represents the diminution of the stratospheric ozone layer due to anthropogenic emissions of ozone-depleting substances. Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth's atmosphere, increasing the amount of carcinogenic UVB light reaching the earth's surface. CFCs, halons and HCFCs are identified as the major causes of ozone depletion.
- *Photochemical oxidation* [kg ethylene equivalent]. Ozone is protective in the stratosphere, but on the ground-level, in high concentration, it is toxic to humans. Photochemical ozone is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. The impact category depends largely on the amounts of carbon monoxide (CO), sulphur dioxide, nitrogen oxide, ammonium and NMVOC (non-methane volatile organic compounds).

It is important to remind that the amortization term of the indirect energy is not considered in this analysis, but it is considered for the modified inventory of the ESA. For the impact assessment, the previously compiled inventory is imported into the LCA software to run the chosen methods. The selected primary and secondary flows from the databases to represent the case study under analysis are summarized in Table 4.15. In particular, the values listed were referred to an *Activity Level* of 100%, which in this case allowed to carry out a more conservative analysis.

Furthermore, other key exchanges were added in order to make the process as realistic as possible, such as: seabed occupation (the FLNG platform is 432 meters long and 66 meters wide), offshore wells for NG production and two items accounting for the transportation of diesel, food, chemicals and materials from the shore to the FLNG platform (a distance of 400 kilometers was chosen, since the platform is located 200 kilometers offshore).

Table 4.15: Modelled exchanges with the biosphere and technosphere using *Ecoinvent v3.9* datasets.

Exchange name	Amount	Location	Unit	Type	Categories
market for steel, chromium steel 18/8, hot rolled	$1,92 \cdot 10^{-3}$	GLO	kilogram	technosphere	
market for aluminium alloy, AlMg3	$1,99 \cdot 10^{-4}$	GLO	kilogram	technosphere	
market for aluminium oxide, metallurgical	$3,21 \cdot 10^{-6}$	RoW	kilogram	technosphere	
market for zeolite, powder	$6,81 \cdot 10^{-6}$	GLO	kilogram	technosphere	
market for activated carbon, granular	$1,29 \cdot 10^{-10}$	GLO	kilogram	technosphere	
market for ethylene glycol	$1,55 \cdot 10^{-3}$	GLO	kilogram	technosphere	
market for diethanolamine	$1,34 \cdot 10^{-3}$	GLO	kilogram	technosphere	
market group for diesel	$2,84 \cdot 10^{-4}$	GLO	kilogram	technosphere	
market for lubricating oil	$9,77 \cdot 10^{-7}$	RoW	kilogram	technosphere	
market for transport, freight, sea, container ship	$1,26 \cdot 10^{-3}$	GLO	ton kilometer	technosphere	
market for transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas	$1,14 \cdot 10^{-4}$	GLO	ton kilometer	technosphere	
market for offshore well, oil/gas	$1,32 \cdot 10^{-5}$	GLO	meter	technosphere	
Water, salt, ocean	$5,10 \cdot 10^{-2}$		cubic meter	biosphere	Natural resource, in water
Nitrogen oxides	$4,16 \cdot 10^{-4}$		kilogram	biosphere	Air
Carbon monoxide, fossil	$2,10 \cdot 10^{-5}$		kilogram	biosphere	Air
NMVOC, non-methane volatile organic compounds	$2,70 \cdot 10^{-6}$		kilogram	biosphere	Air
Sulfur oxides	$6,00 \cdot 10^{-7}$		kilogram	biosphere	Air
Carbon dioxide, fossil	$3,47 \cdot 10^{-2}$		kilogram	biosphere	Air
Particulate Matter, > 2.5 um and < 10um	$9,00 \cdot 10^{-7}$		kilogram	biosphere	Air
Gas, natural	1,24		Sm^3	biosphere	Natural resource, in ground

Ethane	$3{,}15 \cdot 10^{-6}$	kilogram	biosphere	Air
Butane	$4{,}40 \cdot 10^{-6}$	kilogram	biosphere	Air
Methane, fossil	$9{,}12 \cdot 10^{-3}$	kilogram	biosphere	Air
Occupation, seabed, infrastructure	$7{,}19 \cdot 10^{5}$	square meter-year	biosphere	Natural resource, land
BOD5, Biological Oxygen Demand	$1{,}51 \cdot 10^{-6}$	kilogram	biosphere	Water, ocean
Oils, unspecified	$5{,}87 \cdot 10^{-7}$	kilogram	biosphere	Water, ocean
Suspended solids, unspecified	$2{,}21 \cdot 10^{-6}$	kilogram	biosphere	Water, ocean
Mercury II	$5{,}00 \cdot 10^{-12}$	kilogram	biosphere	Soil, industrial

For evaluating not only the FLNG production and processing steps but also its entire supply chain, additional exchanges are required. In particular, Table 4.16 shows the datasets selected from the database to represent these additional steps. It can be noticed that the global (GLO) geography was chosen for each voice. That is, a representation of the average global production of each activity. Ideally, the global dataset is created to accurately reflect the global average conditions based on international data. In this way, a more general scenario was simulated for the FLNG supply chain.

Table 4.16: Steps of the FLNG full supply selected from *Ecoinvent v3.9* database.

Liquefied natural gas, full supply chain from FLNG Product: 1 standard cubic meter of natural gas			
Steps of the FLNG supply chain	**Location**	**Reference process**	**Comments**
Liquefied natural production, via floating facility	GLO	This study	
LNG carrier transportation	GLO	*Market for transport, freight, sea, tanker for liquefied natural gas*	A distance of 10.000 km for transporting $8{,}50 \cdot 10^{7}$ tons of NG was considered
Regasification	GLO	*Evaporation of natural gas, import from MY*	This process refers to [46], according to which the technology mix in Europe is made up of 60% ORV. The selection of the regasification technology depends on the geographical and meteorological conditions of the specific location
NG onshore transportation (pipelines, national network)	GLO	*Market for transport, pipeline, onshore, long distance, natural gas*	A distance of 300 km for transporting $8{,}50 \cdot 10^{7}$ tons of NG was considered

The impact assessment of the production via FLNG platforms and the full supply chain are reported in Table 4.17 and schematically represented in Figure 4.5, where the two analysis are compared.

Table 4.17: Impact assessment of FLNG production and processing and the extended supply chain.

	FLNG Production	**FLNG supply chain**	**Units**
Reference product	1	1	Sm^3_{NG}
CED; energy resources: non-renewable; energy content (HHV)	50,0	53,8	MJ_{eq}/Sm^3
Acidification	0,000314	0,00417	kg SO_{2eq}/Sm^3
Global warming (GWP100)	0,314	0,609	kg CO_{2eq}/Sm^3
Freshwater aquatic ecotoxicity	0,055	0,154	kg 1,4-DCB_{eq}/Sm^3
Marine aquatic ecotoxicity	62,91	276,4	kg 1,4-DCB_{eq}/Sm^3
Terrestrial ecotoxicity	0,0094	0,0114	kg 1,4-DCB_{eq}/Sm^3
Abiotic depletion potential (ADP): fossil fuels	45,00	48,36	MJ/Sm^3
Eutrophication	0,0001	0,00066	kg PO_{4eq}/Sm^3
Human toxicity	0,394	0,665	kg 1,4-DCB_{eq}/Sm^3
Abiotic depletion potential (ADP): elements (ultimate reserves)	$4{,}22\cdot10^{-7}$	$1{,}54\cdot10^{-6}$	kg Sb_{eq}/Sm^3
Ozone layer depletion	$2{,}46\cdot10^{-10}$	$5{,}325\cdot10^{-8}$	kg CFC-$11_{eq}/Sm^3$
photochemical oxidation	$7{,}64\cdot10^{-5}$	0,00029	kg $ethylene_{eq}/Sm^3$

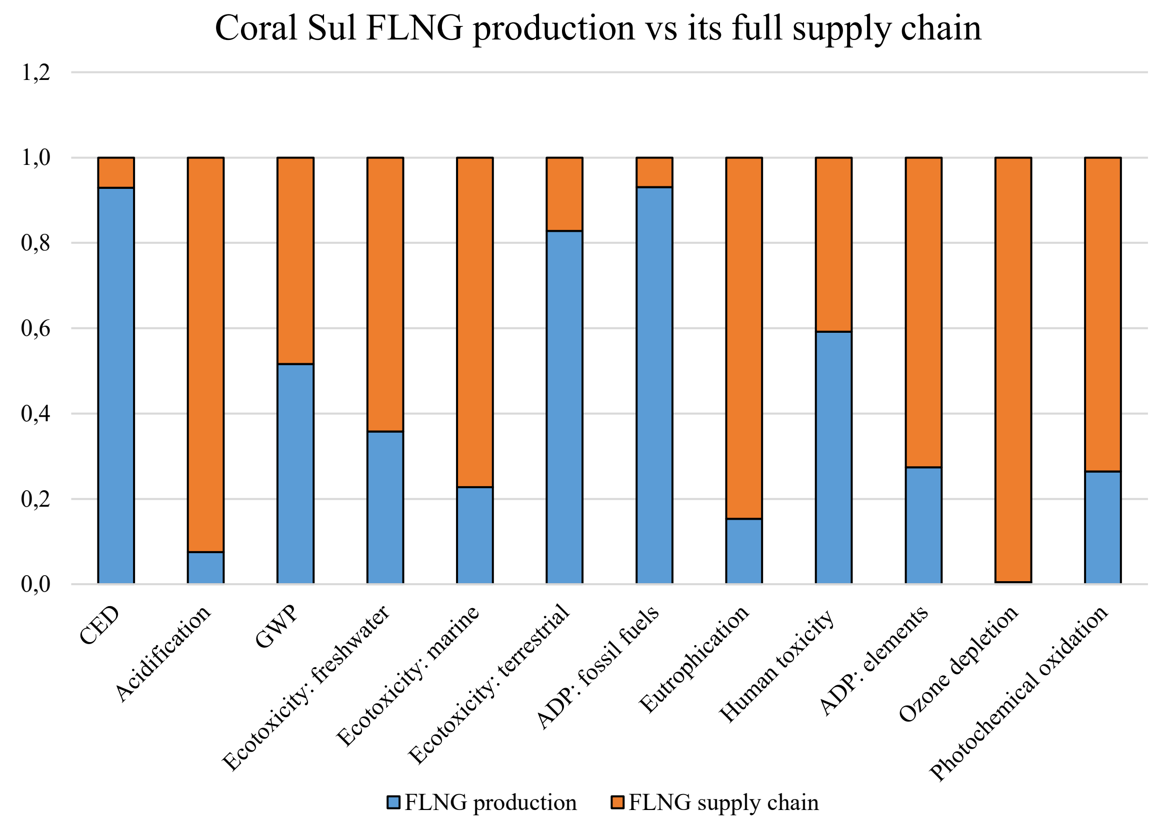

Figure 4.5: Comparison of LCA results of FLNG production and its full supply chain.

As expected, considering extended boundaries and additional steps lead to higher values of each impact category. For instance, higher contributions come from the LNG carrier steps, which due to high sulphur dioxide and nitrogen oxides emissions, considerably increase the *acidification* and *eutrophication categories*. Moreover, it is interesting to note *ozone depletion*, which heavily depends on refrigerants utilization. That is why this value results to be almost zero for the platform under study: its liquefaction process employs ethane and butane instead of compounds such as Halon 1211, Halon 1301, and R10 among others. Nevertheless, these refrigerant are used in other steps of the chain (i.e., pipelines transportation), leading to higher values. On the other hand, discounting on the CED of the FLNG production and its chain the high heating value (HHV) of the produced LNG (i.e., 40,5 MJ/m^3), it can be observed that the GER is almost entirely dependent on the production phase.
As mentioned above, the scope includes benchmarking FLNG against other LNG production processes. For this purpose, two LNG processes were selected: the global one (as a more general referential case) and the one which describes LNG production occurring in Malaysia (MY). The latter dataset was chosen since it includes, in its LNG produced mix, also the one coming from FLNG facilities (i.e., Petronas I e II) which are located in Malaysia. For this analysis, the boundary goes from extraction to liquefaction. The results are shown in Fig. 4.6, where each value is normalized with respect to the FLNG platform used as case study.

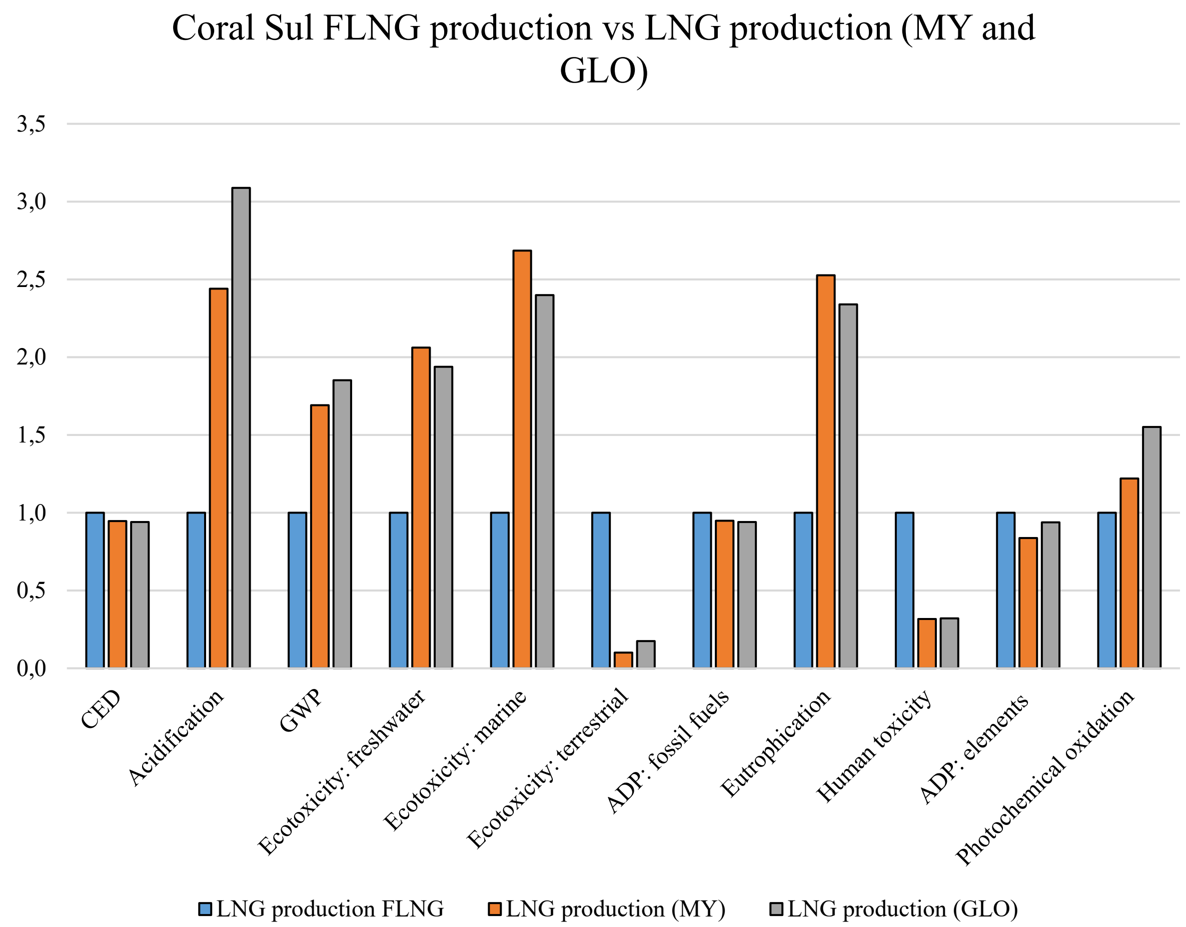

Figure 4.6: Comparison of LCA results of three LNG production processes: Global, from Malaysia, from the studied FLNG platform (Coral Sul).

Discounting on the CED and *fossil ADP* values the HHV of the produced LNG (40,5 MJ/m^3 for the FLNG and 40 MJ/m^3 for the two LNG), it is interesting to note that the three processes are characterized by similar values (Fig. 4.6). On the other hand, the FLNG GWP is almost two times lower. This can be attributed to the lower direct energy demand (due to the high efficiency of the technologies employed, especially for liquefaction) which is much lower compared to the processes conventionally found on the market. As a consequence, the GWP is necessarily lower due to a lower amount of emissions, which represents a huge advantage for energy-optimized FLNG facilities. Indeed, according to the results, the GWP related to the LNG production processes (MY and GLO) is most affected by the exchanges of *natural gas, burned in gas turbine*.

The other impact categories present almost the same values, but not negligible differences can be observed for *ecotoxicity (freshwater, marine* and *terrestrial*), *acidification*, *eutrophication* and *human toxicity*. *Ecotoxicity*, both for *freshwater* and *marine*, results to be higher for the MY and GLO processes, due to the presence of vanadium. Vanadium is a biosphere flow associated to the *municipal solid waste* activity, which is included in the *petroleum and gas production* one. *Terrestrial ecotoxicity*, on the other hand, is higher for the FLNG probably due to the greater steel amount employed in the facility. That is, compared to traditional onshore NG production processes, the FLNG heavily relies on large quantities of steel for its infrastructure and does not require cement or concrete (which then have lower environmental footprint). Indeed, steel production includes chromium primary flows to the biosphere, which, in this case, is the main reason for the higher values of this impact category.

NO_x and SO_2 flows are higher for both the GLO and MY process. The consequences of these biosphere flows, are higher *acidification* and *eutrophication* values. In particular, the latter, is also affected by greater phosphate flows. Again, NO_x and SO_2 flows are lower for FLNG probably due to its low energy-demand liquefaction processes. Finally, the FLNG platform registered a higher *human toxicity* level, which is consequence also of the involved chromium flows.
As introduced, nowadays, about the 70% of NG is mainly transported by pipelines, whereas the remaining part through the liquefied form. Therefore, comparing FLNG with the conventional NG and LNG supply chains, resulted to be mandatory for the purpose of the thesis.
Table 4.18 and Table 4.19 show the different steps of the NG and LNG supply chain, respectively. In this case, the boundaries chosen for the analysis go from production to NG distribution through the national network. The supply chain of the FLNG platform has been already described in Tab. 4.16.
As for the FLNG/LNG chains, an offshore and onshore pipelines length of 580 km and 9420 km, respectively, was chosen for NG supply chain in order to simulate the transportation from the Rovuma basin to the Panigaglia receiving terminal.

Table 4.18: Steps of the NG full supply selected from *Ecoinvent v3.9* database.

Natural gas offshore production, full supply chain Product: 1 standard cubic meter of natural gas			
Steps of NG supply chain	**Location**	**Reference process**	**Comments**
NG production and processing	US	*Petroleum and gas production, offshore*	United States was chosen for this voice since a global one is not present on the database. The US is the largest producer of NG in the world.
NG offshore transportation (pipelines)	GLO	*Market for transport, pipeline, offshore, long distance, natural gas*	A distance of 580 km for transporting $8{,}50 \cdot 10^7$ tons of NG was considered
NG onshore transportation (pipelines)	GLO	*Market for transport, pipeline, onshore, long distance, natural gas*	A distance of 9420 km for transporting $8{,}50 \cdot 10^7$ tons of NG was considered

Table 4.19: Steps of the LNG full supply selected from *Ecoinvent v3.9* database.

Liquefied natural gas production, full supply chain from LNG Product: 1 standard cubic meter of liquefied natural gas			
Steps of LNG supply chain	**Location**	**Reference process**	**Comments**
LNG production and processing	GLO	*Market for natural gas, liquefied*	
LNG carrier transportation	GLO	*market for transport, freight, sea, tanker for liquefied natural gas*	A distance of 10.000 km for transporting $8{,}50 \cdot 10^7$ tons of NG was considered

Regasification	GLO	*evaporation of natural gas, import from MY*	
NG onshore transportation (pipelines, national network)	GLO	*market for transport, pipeline, onshore, long distance, natural gas*	A distance of 300 km for transporting $8{,}50 \cdot 10^7$ tons of NG was considered

Figure 4.7 shows the results obtained from the LCA, which were normalized with respect to the FLNG's values.

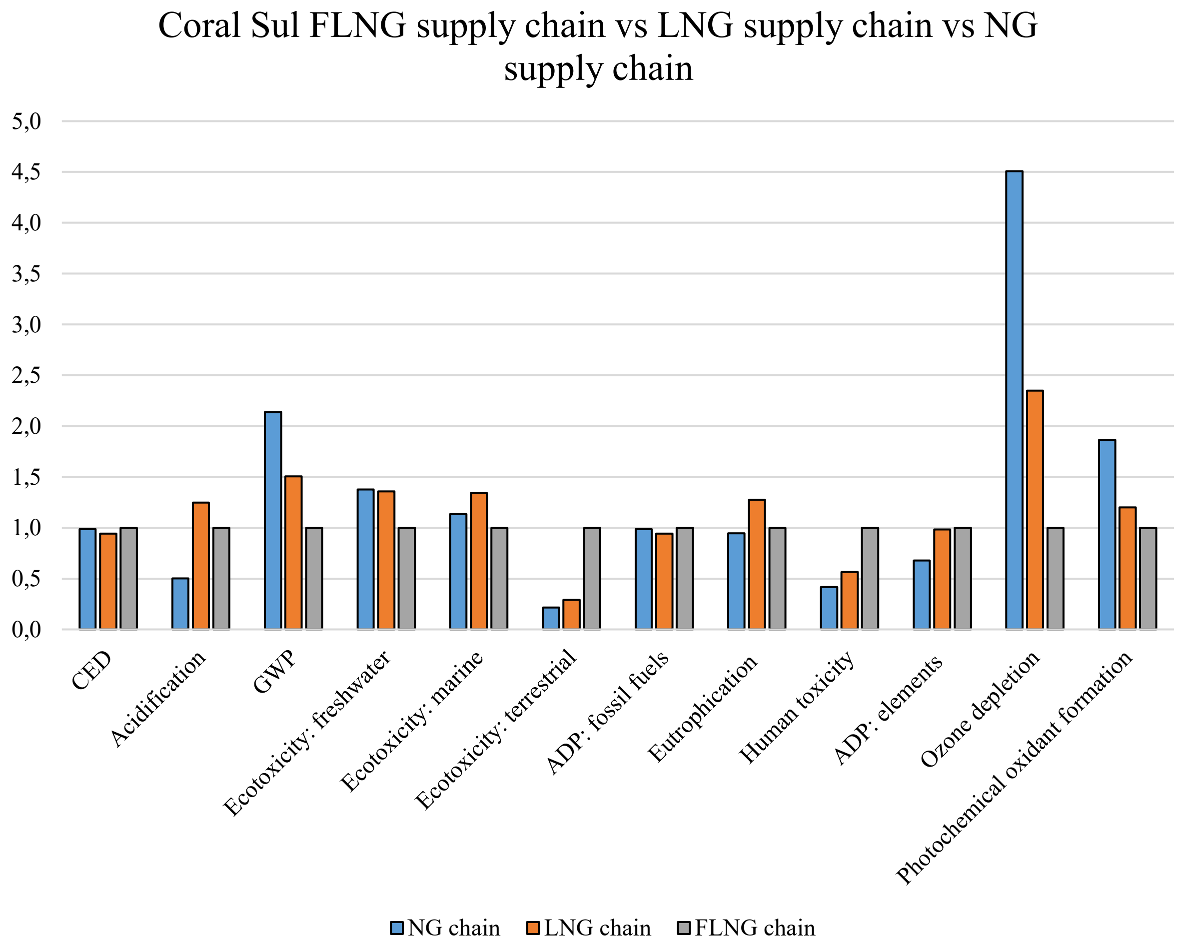

Figure 4.7: Comparison of LCA results of three supply chains: NG, LNG and FLNG.

The analysis shows that similar values are obtained for CED and *fossil ADP* (to the produced NG, as for the LNG, it is associated, according to the database, a HHV of 40 MJ/m^3 which has to be discounted on the CED and *fossil ADP* values in order to compare the different processes). Lower values of *acidification* characterize the NG chain due to lower sulphur dioxide and nitrogen oxides emissions, which, indeed, are mainly derived from the LNG carrier transportation. *Ecotoxicity* results to be quite similar for the *freshwater* and *marine* categories. On the other hand, the *terrestrial* one is considerably higher for FLNG, due to the chromium employed for steel production.

The latter, is also the reason why the *human toxicity*, characterizing the FLNG chain, is almost two times the ones of NG and LNG. Lower values are reached by the NG chain both for *eutrophication* and *elements ADP*. In particular, the latter was found to be higher for FLNG and

NG due to higher primary flows to the biosphere of tellurium and gold, employed in the regasification process. On the contrary, *photochemical oxidation* is higher for the NG chain due to higher nitrogen oxides and ethane emissions, which mainly derive from the pipelines contribution. *Ozone depletion* presents a huge difference between the three chains: FLNG reaches the lowest value due to its liquefaction process which does not include refrigerants application, contrary to the conventional LNG process. Nevertheless, even though LNG production requires higher amounts of refrigerants (which entails higher *ozone depletion)*, the main difference between the three compared cases comes from the onshore pipelines contribution, whose length is considerably higher for the NG chain. Finally, it is interesting to note that the *GWP* significantly differ among the studied cases; LNG and NG values are 1,5 and 2 times greater, respectively, than the FLNG one. These values can be explained by considering the fugitive methane emissions. In particular, even though according to the environmental reports consulted in this work [68] no fugitive methane emissions are registered for the FLNG platform, they were accounted in the present study as the 1% of the extracted NG.
On the other hand, following the *Ecoinvent* database, according to [46], fugitive methane emissions of 0,00204 and 0,0017 kg_{CH4}/ton·km were considered for the onshore and offshore pipelines transportation, respectively. Therefore, depending on the transportation distance, as shown in Figure 4.8, the most favorable method for transporting NG (in terms of GWP) changes. In particular, FLNG results to be the most recommended one when long distances are covered. On the contrary, pipelines result to be the best option for short and medium distances. It was found that lower GWP associated to the upstream and midstream phase of FLNG can be obtained for distances over 2500 kilometers, where trade-offs with compressed NG pipelines occur (see Fig. 4.8).

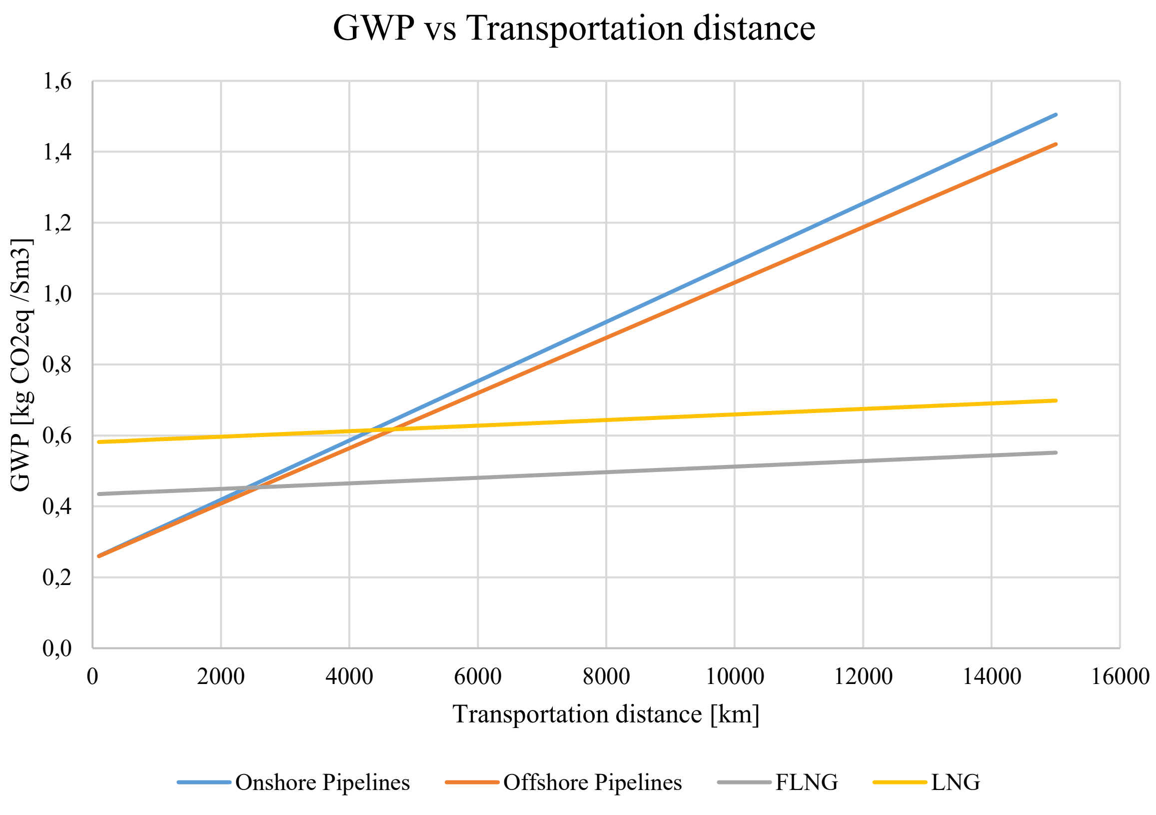

Figure 4.8: GWP associated with the three NG supply chains as a function of transportation distance.

The environmental impacts of NG utilization and its supply chain, involved both direct and indirect emissions. In particular, the latter, were assessed through the study performed in this thesis, which embraced the upstream and midstream phases of three different supply chains. In order to include direct emissions (the end-user) NG combustion must be considered. For this purpose, an emission factor of c. 1,92 kg CO_2 per standard cubic meter of NG was taken, according to [70]. As a result, Fig. 4.9 shows for each column, the sum of the direct and indirect emissions related to 1 Sm^3 of NG, in order to highlight the contribution of the supply chain with respect to the final use.

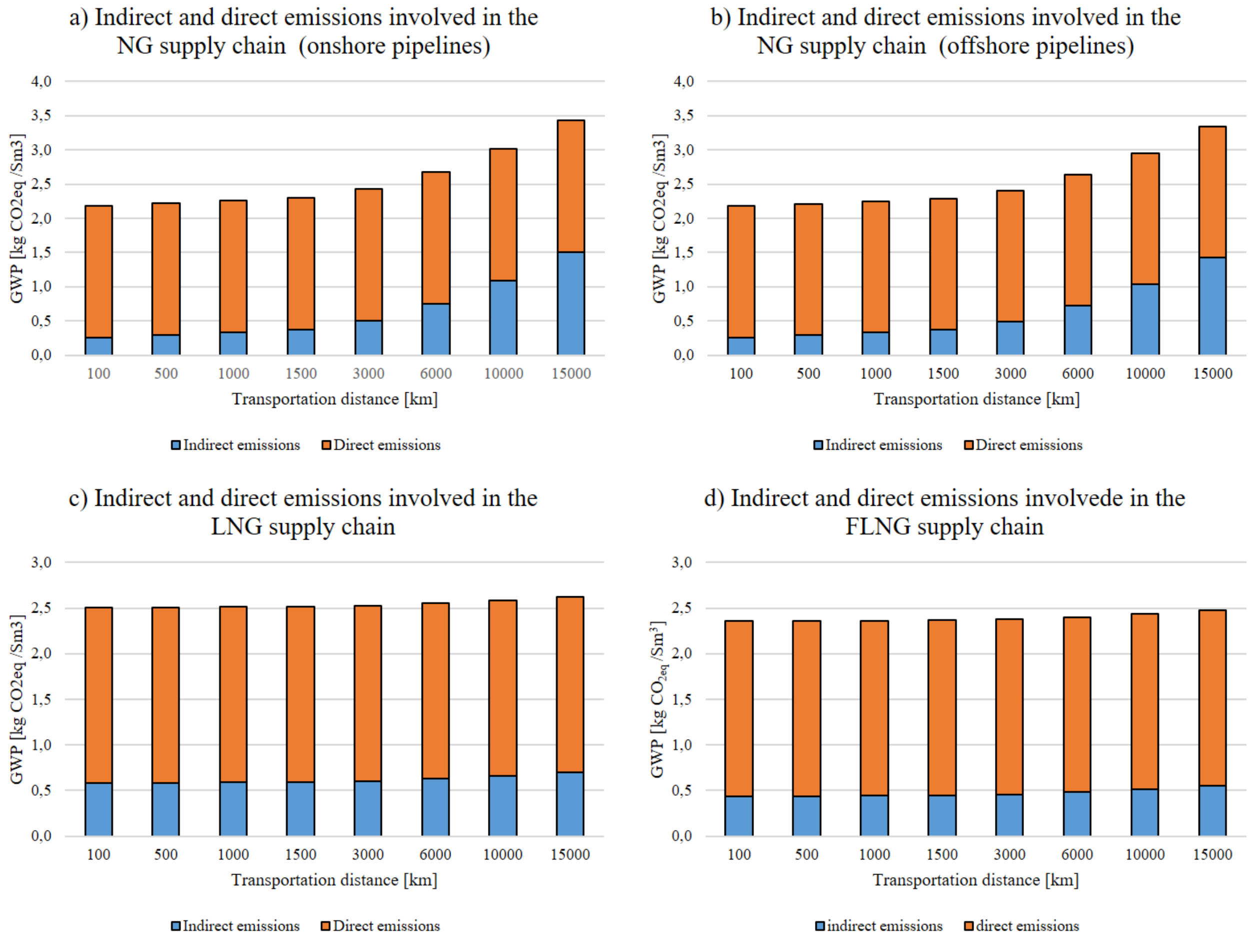

Figure 4.9: Direct and indirect emissions involved in the four NG supply chains: NG (a) onshore and b) offshore), c) LNG, and d) FLNG.

4.4.2 Energy sustainability analysis (ESA)

As LCA, ESA is a methodology for investigating the sustainability of a process, but in this case, from an energetic perspective. In particular, ESA is based on the calculation of three main parameters, which can help to characterize the energy sustainability of the specific technology at two different temporal levels: short-term (ESI) and long-term (EROI and EPT).

Through the present study, the performance of the FLNG platform is compared to the conventional LNG and NG producing technologies and their supply chain.

In the first instance, the production and processing phase of raw NG performed by Coral Sul along its lifespan is investigated, considering an *Activity Level* of 100%. Hence, the space boundaries of this first ESA go from extraction to liquefaction.

Table 4.20 summarizes the primary energy sources involved in this first analysis, and the consequent evaluation of the *net* and *useful energy* flows (Eq. 3.3 – 3.4).

Table 4.20: Energy terms related to the FLNG platform along its lifespan (*Activity Level* 100%)

Energy terms related to the FLNG (Activity Level 100%)		
Primary Energy [MJ]		$5{,}82\cdot10^{12}$
Produced Energy [MJ]		$4{,}68\cdot10^{12}$
Direct Energy [MJ]	Heat [MJ]	$6{,}30\cdot\ 0^{9}$
	Power [MJ]	$1{,}77\cdot10^{11}$
Indirect Energy [MJ]	Materials [MJ]	$1{,}60\cdot10^{10}$
	Chemicals [MJ]	$2{,}14\cdot10^{10}$
	Maintenance [MJ]	$2{,}40\cdot10^{9}$
	$E_{\text{ind to produce Edir}}$ [MJ]	$4{,}82\cdot10^{8}$
	Construction [MJ]	$2{,}40\cdot10^{9}$
	Decommissioning [MJ]	$2{,}40\cdot10^{9}$
	$E_{\text{ind diesel transportation}}$ [MJ]	$1{,}39\cdot10^{6}$
	$E_{\text{ind chemical/food/material transportation}}$ [MJ]	$1{,}93\cdot10^{7}$
	Labor [MJ]	$1{,}67\cdot10^{8}$
	Amortization [MJ]	$3{,}74\cdot10^{10}$
E_{net} [MJ]		$4{,}50\cdot10^{12}$
E_{ind} [MJ]		$8{,}26\cdot10^{10}$
E_{useful} [MJ]		$4{,}41\cdot10^{12}$
LNG production [kg]		$8{,}50\cdot10^{10}$

Data about the *LNG production* term were found on literature [59]. Moreover, for converting the tons of LNG produced in *Produced Energy*, a low heating value (LHV) of 55 MJ/kg was considered.

For estimating the values of *Primary* and *Thermal Energy*, the inventory data of the previous section was used. As shown in Table 4.20, for evaluating the *Direct Energy*, both heat and power expenses are needed. The former, is the sum of two contributions: diesel and fuel gas, the amounts were reported in the inventory analysis (Tab. 4.13). In order to convert the kilograms of diesel in MJ, a LHV of 41 MJ/kg was employed. For electricity, the declared energy consumption of the FLNG platform of 256 kWh was used. Therefore, knowing the annual production of the FLNG platform (3,4 mtpa) and its lifespan, it is possible to estimate the required *direct energy*. *The indirect energy* is the sum of several contributions, which were calculated following different estimation approaches.

Materials and *chemicals* contributions were found using Eq. 3.1 and 3.2, the kilograms are known from the inventory analysis, whereas the CED values were available and taken from the *Ecoinvent v3.9* database. *Decommissioning*, *Maintenance* and *Construction*, were considered to be the 15% of the aggregated *materials* estimate(in energy terms), according to [71]. The *amortization* term takes into account not only the materials, but also the chemicals needed for replacing the entire facility at the end of its useful life (hence guaranteeing the sustainability of the energy supply). For this reason, this term was calculated as the sum of the *materials* and *chemicals* aggregated energy footprint.
The term *Labor* was evaluated considering 350 working people (according to the maximum hosting capacity declared by the FLNG platform living quarter), requiring for their human needs 2500 kcal per day. The energetic expenses related to the food supply chain was considered by multiplying the obtained *labor* value by a factor of 5, according to the average values which can be found on literature [52]. Finally, *indirect energy* expenses for transporting diesel, food, chemicals and materials, and for "producing" the *direct energy* were obtained by finding the respective CED values (Table 4.15) on the *Ecoinvent v3.9* database. Moreover, for that purpose, in order to estimate the kilograms of food, a referential value of 2400 kcal/kg has been considered (according to [72]).
As a summary, the different *indirect energy* contributions are listed in Table 4.21 and schematically represented in Figure 4.10.

Table 4.21: *Indirect Energy* contributions.

Indirect Energy contributions	% of Indirect Energy
Materials	19,36%
Chemicals	25,87%
Maintenance	2,90%
E_{ind} to produce Edir	0,58%
Construction	2,90%
Decommissioning	2,90%
$E_{ind\ diesel\ transportation}$	<0,01%
$E_{ind\ chemical/food/material\ transportation}$	0,02%
Labor	0,20%
Amortization	45,24%

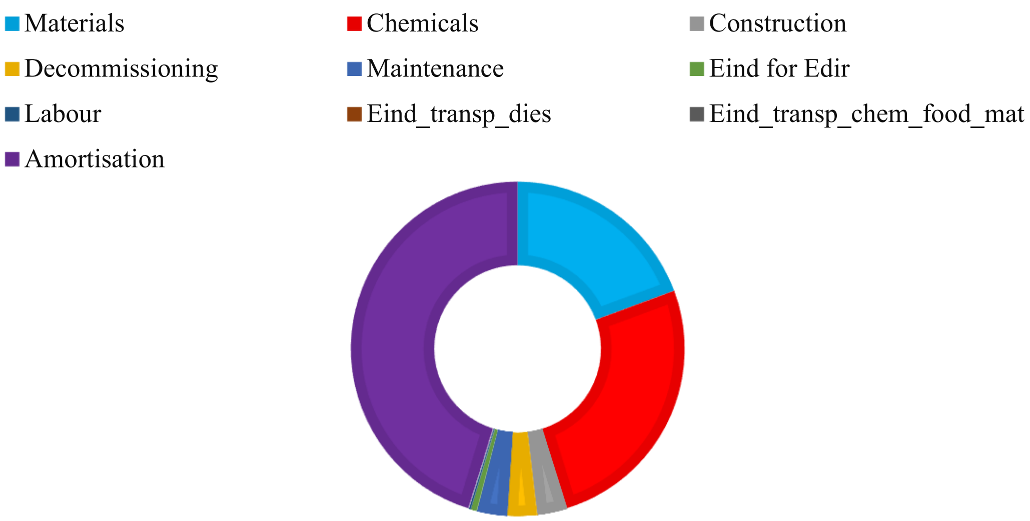

Figure 4.10: *Indirect energy* contributions.

Therefore, employing the different energy values listed in Table 4.20, ESI, EROI and EPT can be calculated using Eq. 3.5 - 3.7. The results are summarized in Table 4.22.

Table 4.22: ESA results of the FLNG process, considering an *Activity Level* of 100%.

ESA FLNG (Activity level of 100%)	
ESI	24,70
EROI	54,46
EPT [years]	0,46

As mentioned, in order to take into account a more realistic and conservative scenario, an *Activity Level* of 70% is considered, and a second ESA on the FLNG is performed. Since in this scenario lower production is considered, the values of several energetic terms change due to this tested condition. Table 4.23 shows which terms are changing comparing to the previous case (Table 4.20).

Table 4.23: Energy terms evaluated for an *Activity Level* of 70%.

Energy terms of the FLNG (Activity Level 70%)	
Primary Energy [MJ]	$4{,}07 \cdot 10^{12}$
Produced Energy [MJ]	$3{,}28 \cdot 10^{12}$
Direct Energy [MJ]	$1{,}33 \cdot 10^{11}$
E_{net} [MJ]	$2{,}69 \cdot 10^{12}$
E_{ind} [MJ]	$8{,}07 \cdot 10^{10}$

Due to the hypothesized reduced production, the extracted *primary energy* (and consequently the *produced* one) are lower compared to the previous case. The same behavior can be observed for the *direct energy* (less heat and power are required) and for the *indirect energy* (the *indirect energy* for producing the *direct* one, since the latter is lower, decreases).
In this regard, Figure 4.11 represents a sensitivity analysis, which shows the behavior of ESI, EROI and EPT when the *Activity Level* varies from 10% to 100%.

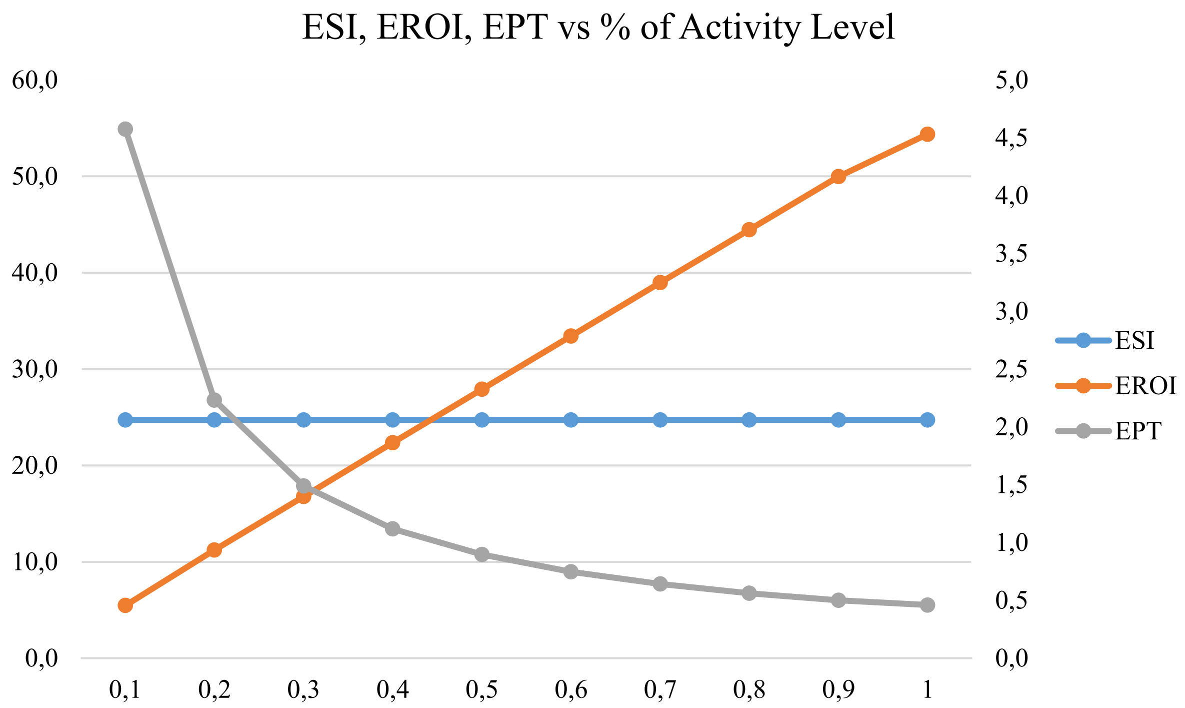

Figure 4.11: ESI, EROI and EPT for different *Activity Levels*.

Therefore, considering the specific case study for which an *Activity Level* of 70% was selected, according to Fig. 4.11, new ESA indicators results were obtained and summarized in Table 4.24.

Table 4.24: ESA results of the FLNG process, considering an *Activity Level* of 70%.

ESA FLNG (Activity level of 70%)	
ESI	24,7
EROI	39,0
EPT [years]	0,6

As expected, the ESI remains constant since both the *produced energy* and the *direct energy* change as a consequences of one another. Indeed, it was assumed that when outages occur and production stops, *direct energy* requirements are very low. Therefore, these two energy parameters resulted almost to be proportional, leading, as a consequence, to a constant ESI. On the other hand, the EROI is lower compared to the case of 100% of *Activity Level*, since the *net energy* decreases. It is important to note that for lower *Activity Levels*, the *indirect energy* decreases as well, hence higher values of EROI should be reached. Nevertheless, its variation is negligible since it depends only on the *indirect energy* for producing the *direct* one, which

has a small contribution on the *indirect energy* term (Fig. 4.10). That is why overall, the EROI decreases. Finally, the EPT indicator increases since for lower production levels, more time is needed for compensating the initial energy investments.
As for the LCA, investigating the entire supply chain of the FLNG platform (an *Activity Level* of 70% was considered for this purpose) was objective of the thesis. The *direct* and *indirect energy* expenses of each phase of the supply chain, required for performing the calculation of ESI, EROI and EPT, are listed in Table 4.25.

Table 4.25: *Direct* and *Indirect Energy* expenses for each step of the FLNG supply chain (*Activity Level* of 70%).

FLNG Supply Chain (Activity Level 70%)			% of Primary Energy	Reference process
FLNG (Production and Processing)	Direct Energy [MJ] Indirect Energy [MJ]	$1{,}33 \cdot 10^{11}$ $8{,}07 \cdot 10^{10}$	6,5	This study
Transportation (LNG Carrier)	Direct Energy [MJ] Indirect Energy [MJ]	$9{,}27 \cdot 10^{10}$ $1{,}02 \cdot 10^{10}$	2,5	*transport, freight, sea, container ship | market for transport, freight, sea, container ship | GLO | ton kilometer | Ecoinvent_cutoff39*
Regasification	Direct Energy [MJ] Indirect Energy [MJ]	$1{,}12 \cdot 10^{10}$ $5{,}22 \cdot 10^{10}$	1,9	*natural gas, high pressure | evaporation of natural gas, import from MY | GLO | cubic meter | Ecoinvent_cutoff39*
NG Distribution	Direct Energy [MJ] Indirect Energy [MJ]	$5{,}85 \cdot 10^{9}$ $1{,}06 \cdot 10^{10}$	0,4	*transport, pipeline, onshore, long distance, natural gas | market for transport, pipeline, onshore, long distance, natural gas | GLO | ton kilometer | Ecoinvent_cutoff39*
Supply Chain	Direct Energy [MJ] Indirect Energy [MJ] Net Energy [MJ]	$2{,}93 \cdot 10^{11}$ $1{,}56 \cdot 10^{11}$ $2{,}99 \cdot 10^{12}$	11,3	

For the FLNG platform, the two terms were calculated as previously mentioned (Tab. 4.23).
On the other hand, for estimating the *direct* and *indirect energy* for the other steps, the datasets contained in *ecoinvent v.3.9* were employed.
For the *transportation*, the *direct energy* expenses were calculated considering both the values found on the database (the datasets of *heavy fuel oil* was converted, using a LHV of 46 MJ/kg into *direct energy* expenses) and the electricity needed for re-liquefying the *boil-off gas* (BOG). In particular, according to [73] for a transportation lasting 20 days, the boil-off rate is the 0,3% per day of the NG transported. Whereas, the specific energy consumption for re-liquefaction was assumed to be 1,27 kWh per 1 kg of BOG.

On the other hand, the *indirect energy* expenses were estimated using the CED associated to the activity, for which a distance of 10.000 km and $5{,}96 \cdot 10^7$ tons of LNG transported were considered. When LNG reaches the terminal, regasification occurs (see Tab. 4.25).
The *indirect energy* is calculated using the CED associated to the process, whereas the *direct energy* was referred to the consumption of the *NG burned in gas turbine*. Finally, the last step, is the NG distribution by pipelines through the national network. The *indirect* and *direct energy* expenses were evaluated through database secondary data, considering the CED value and the MJ of *NG burned in turbine,* respectively.
As a result, from Tab. 4.25 it is interesting to note that the energy consumption of the entire chain corresponds to the 11,3% of the initial NG, namely the *primary energy*. As expected, the most energy demanding stage is the processing one due to the energy-intensive liquefaction process. This percentage results to be slightly lower compared to the values which can be found on literature [73] for the conventional LNG supply chain, which are around the 20%. In particular, according to [73] liquefaction is the most energy demanding part of the LNG process, consuming from the 5 to the 15% of NG going through the process (Fig. 4.12).

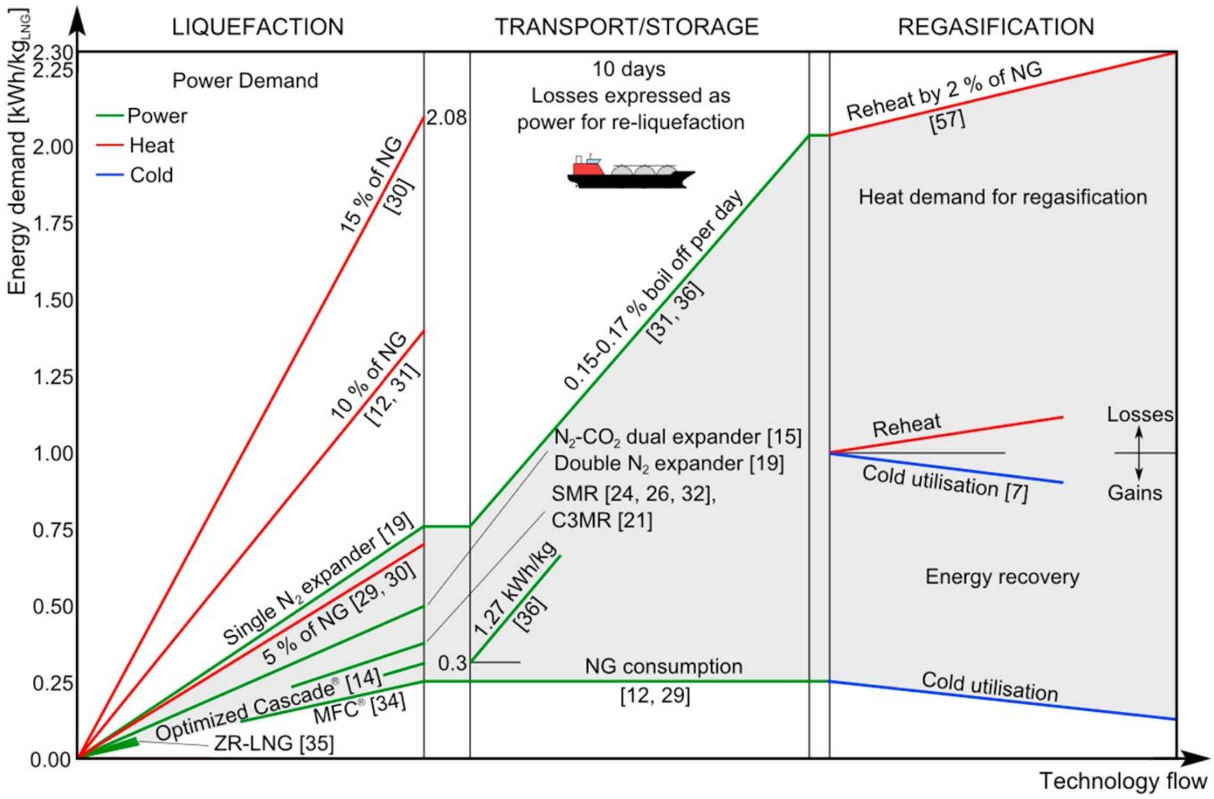

Figure 4.12: Energy demands of LNG process. Figure taken from [73] with modifications.

Again, this difference between the studied FLNG platform and the conventional LNG processes may be justified by the lower direct energy consumption. In particular, specific techniques have been adopted in order to minimize as much as possible the energy needed for liquefaction, since it has the highest potential for decreasing the energy demand [74].
Table 4.26 shows the results obtained for the ESA of the FLNG supply chain under the hypothesized conditions. As expected, adding steps leads to a lower ESI and EROI due to higher energy demand (of the additional steps, which do not increase the *useful energy*). For the same reasons, the EPT increases.

Table 4.26: ESA results of the FLNG supply chain, considering an *Activity Level* of 70%.

ESA FLNG supply chain	
ESI [-]	11,20
EROI [-]	19,20
EPT [years]	1,30

Another goal of the thesis is comparing the FNLG with other NG transportation options: LNG and NG. [75] provides both a literature review and a harmonization of EROI values of the major *Energy Carriers*. EROI evaluation is a popular metric to assess the profitability of energy extraction processes and, therefore, it can be used as a strategy to compare them. As mentioned, the EROI definition is not standard. In particular, [75] defines the EROI as follow:

$$EROI = \frac{Gross\ Energy\ Output}{\sum Energy\ Investments} \tag{4.5}$$

Gross energy output refers to the *produced energy*, whereas *energy investments* are the sum of *direct* and *indirect energy.* Therefore, in order to perform a reasonable comparison between studied FLNG and the literature values of the LNG and NG supply chains [75], the EROI is re-calculated using Eq. 4.5. Moreover, in order to be consistent with the values reported in [75] the system boundaries must be considered from NG extraction to its *point-of-use* (POU). In the case of LNG, the POU includes liquefaction and LNG transportation by LNG carrier. For NG, all the supply chain is taken into account: from extraction to NG distribution by the national network. In the first instance, the FLNG platform was compared to the traditional LNG one. The terms needed for re-calculating FLNG EROI, from NG extraction to LNG carrier distribution are shown in Table 4.27.

Table 4.27: Energy terms related to the FLNG process (*Activity Level* of 70%).

Energy terms (Activity Level 70%)		
Produced Energy [MJ]		$3{,}28 \cdot 10^{12}$
Direct Energy [MJ]	FLNG	$1{,}83 \cdot 10^{11}$
	LNG Carrier	$9{,}27 \cdot 10^{10}$
Indirect Energy [MJ]	FLNG	$8{,}26 \cdot 10^{10}$
	LNG Carrier	$1{,}02 \cdot 10^{10}$
Energy Investments [MJ]		$3{,}68 \cdot 10^{11}$

Using the values from Tab. 4.27 and Eq. 4.5, an EROI of 8,9 was obtained for the FLNG platform. Figure 4.13, according to [75] shows the EROI for the LNG production process which is around 6,3.

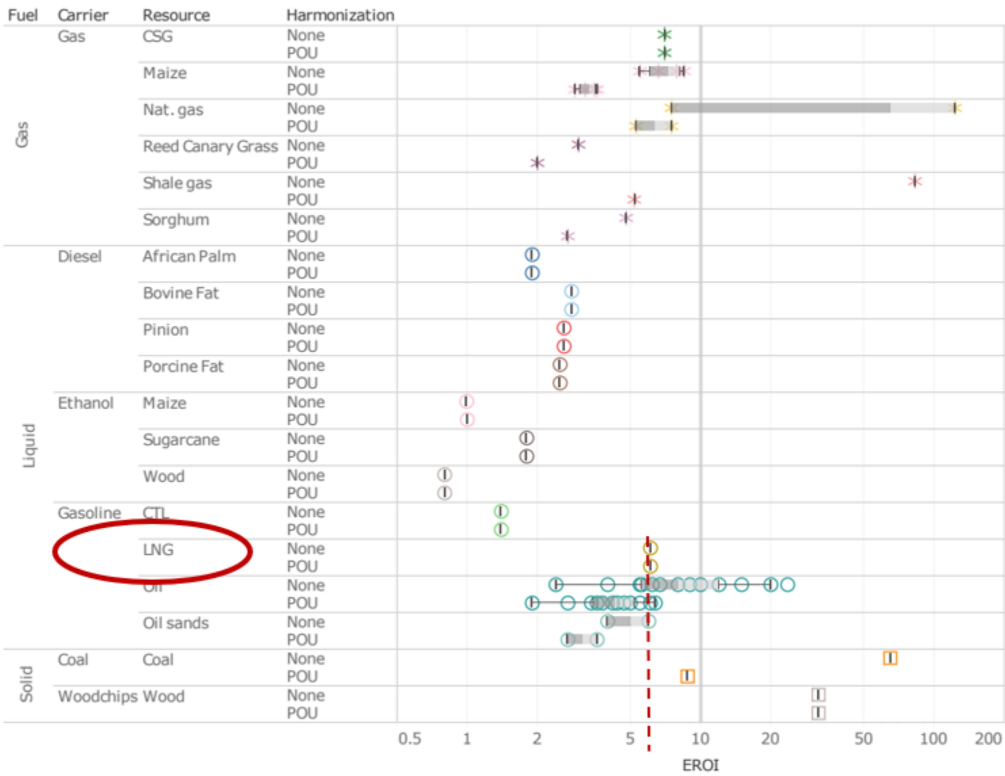

Figure 4.13: EROI values for thermal fuels, respectively, as originally published (Harmonization = "None") and post-harmonization at point of use (Harmonization = "POU"). Figure taken from [75] with modifications.

Similarly, in order to compare the EROI of the FLNG platform to the one of the NG supply chain found on literature, the different energy contributions are re-calculated as shown in Table 4.28. Again the boundaries of the analysis are from NG extraction to NG national distribution by pipelines.

Table 4.28: Energy terms related to the FLNG supply chain (*Activity Level* of 70%).

Energy terms (Activity Level 70%)		
Produced Energy [MJ]		$3{,}28 \cdot 10^{12}$
Direct Energy [MJ]	FLNG supply chain	$2{,}93 \cdot 10^{11}$
Indirect Energy [MJ]	FLNG supply chain	$1{,}56 \cdot 10^{11}$
Energy Investments [MJ]		$4{,}49 \cdot 10^{11}$

Once again, using Eq. 4.5, an EROI of 7,3 was obtained for the FLNG supply chain. Figure 4.14, according to [75] shows the EROI for the conventional NG supply chain which is in the 5÷8 range.

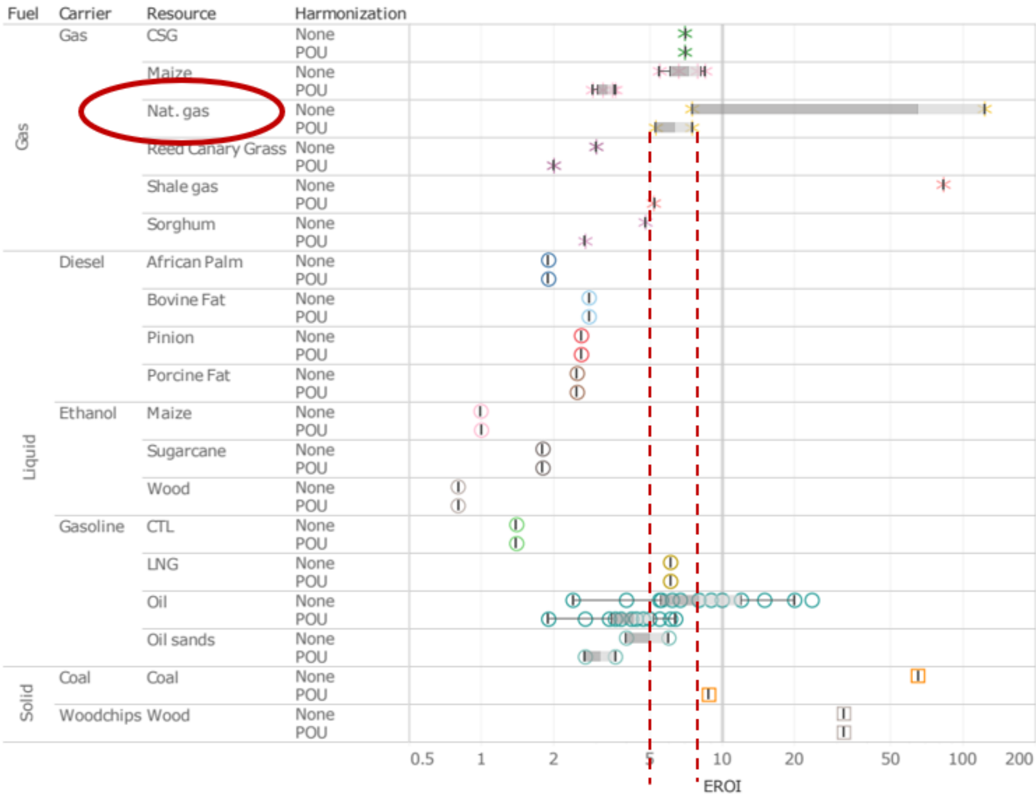

Figure 4.14: EROI values for thermal fuels, respectively, as originally published (Harmonization = "None") and post-harmonization at point of use (Harmonization = "POU"). Figure taken from [75] with modifications.

5. Conclusions

The environmental impacts of full supply chains are gaining relevance for the current climate change mitigation goals. In this thesis, the different NG supply chains were investigated both from an environmental and energetic sustainability perspectives, shedding light on the emerging FLNG facilities. In particular, the Coral Sul FLNG was used as a model case study. In the first instance, the inventory analysis of this structure was performed: the main exchanges with the technosphere and the biosphere were assessed, considering all the life stages and the production patterns. Combining primary (reports, brochures and available disclosed information) and secondary data (obtained from the *Ecoinvent v3.9 cutoff* database), the employed materials for the floating facility resulted to be 11% higher compared to the 220.000 tons officially declared [64]. These calculated additional material will serve to cover possible material expenses, such as maintenance or substitutions, along the lifecycle. Apart from materials, solid/gaseous/liquid emissions were evaluated according to [68].
For assessing the environmental impacts, the life cycle assessment (LCA) technique was employed. A first analysis was carried out over the FLNG platform and its supply chain. As expected, higher values for each impact category, due to an increase of exchanges with the technosphere and the biosphere, were registered when the full chain was considered. In particular, the LNG carrier transportation led to a considerable increase in *acidification* and *eutrophication*. *Ozone depletion* resulted to be almost zero for the floating facility: its liquefaction process employs ethane and butane, instead of the more impactful refrigerant compounds which are normally used. Nevertheless, these refrigerants are exploited in other steps of the chain (i.e. pipelines transportation), leading to higher *ozone depletion* values. On the other hand, discounting the HHV (high heating value) of the produced LNG (i.e., 40,5

MJ/m^3) on the CED values, it was noticed that the obtained GER was almost entirely dependent on the production phase which, therefore, resulted to be the most energy demanding step. Whereas, discounting the same amount on the *fossil ADP*, showed that this category heavily depended both on the FLNG production and on the full chain. The same, can be observed for the GWP, which is strictly dependent on both the FLNG and its chain. Finally, the regasification process was found to be responsible for the higher values of the *elements ADP* reached.
Another aim of the thesis was the comparison between the FLNG and the conventional LNG production processes. The LCA showed that similar values of GER (considering the discounted HHVs, equal to 40 MJ/m^3 for the LNG) were obtained, therefore, from an embedded energy demand point of view, no advantages of using one option or the other were highlighted. The same was noticed for both the *ADP* (*fossil* and *elements*). Nevertheless, the floating facility resulted to be the best option if all the other impact categories were considered, with the exception of *terrestrial ecotoxicity* and *human toxicity*. The high values of these two categories strictly depended on the high amount of steel employed in the FLNG platform. Among the showed results, it was highlighted that the GWP associated to the floating facility was almost two times lower than the conventional LNG processes. As mentioned, according to [53] its energy demand is much lower compared to the LNG processes available on the market. As a consequence, the GWP is necessarily lower due to a lower amount of GHG emissions, which represents a crucial advantage of the FLNG facility.
Finally, over a transportation distance of c. 10.000 km, the three main full supply chains were investigated: FLNG, LNG and NG. First of all, it was highlighted that CED and *fossil ADP* (both discounted on the HHV of the respective produced fuel) were similar for the three chains. Moreover, considering the results for each impact category, it was noticed that there is no a clear advantage of exploiting one chain with respect to the other, since depending on the category, the favorable option changes. Nevertheless, considering the current efforts of society for moving towards a net zero emissions scenario, the GWP can be chosen as selecting criteria between the chains. In this regard, Fig. 4.7 shows that FLNG, for the case study investigated, represents the best option since its value is 1,5 and 2 times lower compared to the LNG and NG chain, respectively. Nevertheless, as represented in Fig. 4.8, the GWP varies as a function of the covered distance, mostly due to the different fugitive methane emissions: a trade-off with the compressed NG pipelines occurs for distances over 2500 km. In other terms, through the study performed, the indirect emissions related to 1 Sm^3 of produced NG were assessed. To take into account the direct emissions due to the utilization of the same amount, NG combustion was considered. An emission factor of 1,92 kg CO_2/Sm^3 was employed for this purpose. As a result, Fig. 4.9 showed the contribution of the indirect emissions with respect to the direct one, in terms of GWP. As expected, the total GWP increased with the covered distance. It was observed that, for the smaller distances, the indirect emissions of the FLNG and the LNG covered a higher percentage on the total GWP, than the NG chains. Nevertheless, when transportation increased, these percentages remained less variable: they passed from c.23% to 27%, and from c. 18% to 22%, for the LNG and the FLNG respectively. On the contrary, a more evident increase was noticed for the NG chains, where the contribution of indirect emissions heavily raised with the covered distance. Indeed, it passed from c.12% to 44%, and from c.12% to 42%, for the onshore and offshore case, respectively. Therefore, due the contribution given by the indirect emissions, this last analysis demonstrated the importance of assessing the environmental impacts of full supply chains.
For investigating the sustainability of processes from an energetic perspective, the ESA methodology was applied. In the first instance, the production and processing phase of Coral Sul were explored, both for an *Activity level* of 100% and for a 70% one. The latter, in particular, aimed to represent a more realistic scenario, which considered the possible outages normally occurring in these facilities. As expected for a lower *Activity Level*, the EROI decreased

(passing from 54,46 to 39,0) since the *net energy*, which has the strongest influence on the index, decreased due to a lower production. The ESI on the other hand, remained constant at 24,7 in the two scenarios since *produced energy* and *direct energy* decreased almost proportionally. Finally, the EPT increased, passing from 0,46 to 0,60 years: more time is needed for compensating the initial energy investments.
Considering an Activity Level of 70%, the entire supply chain of the FLNG platform was evaluated. As expected, adding new steps (i.e., increasing the energy expenditure) led to lower values of ESI and EROI, and higher values of EPT, which reached values of 11,20, 19,20, and 1,3 years, respectively. Tab. 4.25 shows the contribution of each step to the chain in term of percentage of primary energy. Overall, it resulted that the energy consumption of the entire chain corresponded to the 11,3% of the extracted raw NG. The most energy demanding stage is the processing one due to the energy-intensive liquefaction process. This percentage resulted to be slightly lower compared to the values found on literature for the conventional LNG supply chain, which are around the 20%. This, was probably justified by the lower declared direct energy consumption.
Finally, the thesis aimed at comparing the FLNG with the conventional LNG and NG supply chains. [75] provided both a literature review and a harmonization of EROI values of the major *energy carriers*. EROI evaluation is a popular metric to assess the profitability of energy extraction processes and, therefore, it can be used as a strategy to compare them. Despite the methodological differences in the EROI calculation, the performed ESA showed that the EROI found for the FLNG facility (i.e., 8,9) was slightly higher compared to the conventional LNG production processes, which are characterized by an EROI value of 6,3. On the other hand, for the FLNG supply chain an EROI of 7,3 was obtained. This value resulted to be, according to [75], perfectly in line with the values of EROI associated to the conventional NG supply chain, which are in the 5-8 range. Therefore, from an energetic perspective, in terms of EROI, no clear advantages were highlighted between the exploitation of the investigated supply chains. Whereas, for producing and processing the LNG, the FLNG option resulted to be more advantageous with respect to the conventional LNG processes, as its EROI is about 40% higher.

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