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Gas flaring: an overall analysis and a multicriteria approach to alternatives selection

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Dedicated to all those are forced
to live in the light of flares
instead of in the splendor
of stars shine.

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Abstract

During the last years the problem of gas flaring has become increasingly important in the eyes of the international community: on one hand, satellites allowed to make an estimation of the amounts of flared gas, making clear the enormous waste of resources that this practice constitutes; on the other hand, the ever stronger interest aimed at sustainable development underlines the fact that recovering associated gas could lead not only to economic advantages, but also to environmental and social ones.

This is true especially for low developed countries, where the lack of access to energy is often one of the main obstacles to development.

Suitable technologies to collect and make use of associated gas are many, but very often, in a project aimed to reduce or eliminate gas flaring, the greatest difficulties concern the fact of finding an agreement among the various stakeholders and of selecting an alternative reaching the best degree of sustainability.

Hence, this work aims to show how these difficulties could be softened using the support of a decision-making method based on the Analytic Hierarchy Process once an appropriate set of indicators allowing to evaluate and to compare different alternatives has been defined.

Moreover, an application of the model to a real case allowed to underline its principal strenghts and weaknesses, leading to the conclusion that a selection among different alternatives based only on economic factors does not necessary leads to identify the alternative that gives best performances in terms of sustainability.

Keywords gas flaring, *associated petroleum gas*, sustainability, *decision method*, Analytic Hierarchy Process, *Russia*

Estratto in lingua italiana

Gas flaring: da problema a opportunità

Con l'espressione *gas flaring* ci si riferisce alla combustione in torcia del gas associato, ossia alla combustione del gas naturale che in molti casi è presente nei giacimenti petroliferi, e che pertanto è necessario estrarre al fine di ottenere il petrolio come prodotto principale desiderato.

I vincoli che spesso portano a considerare il gas associato come un prodotto privo di valore, che deve pertanto essere smaltito mediante il rilascio in atmosfera (*venting*) o la combustione (*flaring*), possono essere di diverso tipo, e in generale possono essere suddivisi in tre categorie: quelli relativi a problematiche di mercato, quelli relativi alla mancanza di esperienza o di risorse da investire da parte dei produttori e quelli di natura puramente tecnica.

Il contesto globale

La pratica del gas flaring costituisce un enorme spreco di energia: secondo le stime della NOAA[1] nel 2010 sono stati bruciati circa 134 miliardi di metri cubi di gas associato, che in termini energetici corrispondono a più di $120 Mtep$, ossia a circa l'1% della produzione energetica mondiale.

La maggior parte del gas flaring avviene in soli 20 paesi del mondo, molti dei quali sono paesi in via di sviluppo (come ad esempio Angola o Nigeria), che figurano tra i detentori delle maggiori riserve di gas e petrolio, anche perché, spesso in questi paesi non esiste una legislazione che miri a contrastare la pratica o una rete affidabile da utilizzare per il trasporto del gas.

Per comprendere meglio l'entità del fenomeno, si pensi che in alcuni paesi (ad esempio Iraq, Angola, Nigeria) la quantità di gas bruciato in torcia costituisce una percentuale molto rilevante della produzione utile di gas del paese stesso. Inoltre, ipotizzando di convertire il gas in energia elettrica mediante l'utilizzo di turbogas in ciclo semplice (nell'ipotesi, dunque, di un rendimento di conversione piuttosto scarso e pari, in questo caso, al 35%, basata sul fatto che sistemi a più elevato rendimento sarebbero più difficilmente implementabili in paesi in via di sviluppo), si trova che in alcuni paesi la produzione supererebbe di gran lunga quella attuale: ad esempio, in Nigeria nel 2010 si sarebbe potuta ottenere una produzione 4 volte superiore a quella effettiva.

Se ci si riferisce alle tre dimensioni di cui si compone la sostenibilità (economica, ambientale, sociale), è subito evidente che la pratica del gas flaring non può certamente essere considerata accettabile in quanto non soddisfa alcun bisogno di una popolazione nel presente né tantomeno è priva di risvolti negativi per quanto riguarda le future generazioni.

Infatti, dal punto di vista ambientale al gas flaring sono associati effetti negativi sia globalmente che localmente: da un punto di vista globale, la pratica ha come conseguenza l'immissione in atmosfera di enormi quantitativi di CO_2 (280 milioni di tonnellate nel 2010, ossia quasi l'1% delle emissioni totali di origine antropica), mentre da un punto di vista locale sono molte le sostanze nocive rilasciate dalle torce: composti derivanti dalla combustione dello zolfo, NO_x, monossido di carbonio, idrocarburi incombusti, metalli pesanti, ... Queste sostanze possono anche penetrare nel terreno in seguito alle piogge causando problemi all'ecosistema e alle coltivazioni, problemi che nelle aree limitrofe alle fiaccole vanno ad aggiungersi a quelli causati dalle elevate temperature.

Da un punto di vista economico invece, è chiaro che bruciare il gas significa bruciare una risorsa preziosa: infatti a tale pratica è associata una perdita di PIL (Prodotto Interno

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[1] National Oceanic and Atmospheric Administration

Lordo) in media pari allo 0,05% per i 20 paesi maggiormente interessati dal fenomeno (percentuale che cresce fortemente escludendo dalla lista i paesi più sviluppati), con una punta che per la Nigeria supera il 20%.

Infine, il gas flaring è causa di importanti implicazioni sociali: le piogge acide causano il rapido degrado dei tetti in lamiera degli edifici, mentre le emissioni di sostanza dannose possono incrementare il rischio di malattie. Anche il calore, il rumore e l'intenso flusso luminoso sprigionato dalle torce si riflettono sulla salute delle popolazioni limitrofe causando disturbi del sonno, stress, etc...

Inoltre, il ritorno economico derivante dalla vendita del gas porterebbe ai paesi in via di sviluppo vantaggi molto più consistenti di quelli derivanti dagli aiuti internazionali: infatti il valore economico derivante da una vendita del gas per i 20 paesi in cui la pratica è maggiormente impiegata sarebbe in media pari a circa il 270% dell'ammontare degli aiuti internazionali elargiti in loro favore.

Una opportunità per i paesi in via di sviluppo

Il fatto che il gas flaring rappresenti un enorme spreco di risorse perpetuato spesso in paesi non fortemente industrializzati porta a concludere che il recupero del gas associato possa essere visto come una modalità per migliorare le condizioni delle popolazioni che vivono nei paesi detentori di riserve petrolifere. Ciò è particolarmente vero se ci si riferisce a un miglioramento dell'accesso all'energia, ossia, per usare le parole dell'AGECC[2], a un miglioramento dello

> accesso a servizi energetici efficienti, affidabili e disponibili per tutti allo scopo di cucinare, riscaldarsi, usufruire di sistemi di illuminazione, comunicare e produrre beni o altri servizi.

Infatti migliorare l'accesso all'energia significa favorire lo sviluppo, dato che calore ed elettricità sono necessari per assicurare anche assistenza medica, disponibilità di acqua potabile, istruzione e accesso ai sistemi informatici, tanto che, secondo uno studio della Banca Mondiale, sistemi di produzione energetica non affidabili e caratterizzati da scarso rendimento possono causare una perdita di uno o due punti percentuali per quanto riguarda la crescita annua del PIL di una nazione.

Questo fatto risulta ancora più evidente se si pensa che il continente africano ospita il 14% della popolazione mondiale ma consuma solo il 3% dell'elettricità prodotta a livello mondiale, mentre in Europa, ove risiede il 9% della popolazione mondiale, i consumi di elettricità sono pari al 19% della produzione globale.

Inoltre, migliorare l'accesso all'energia mediante lo sfruttamento del gas associato significa migliorare anche le condizioni ambientali e di salute, in quanto si va a sostituire sistemi quali le caldaie a legna, e pertanto a eliminare fonti di emissione, soprattutto per quanto riguarda particolato e incombusti, e a contrastare il fenomeno della deforestazione.

I vantaggi sono particolarmente evidenti per quanto riguarda le categorie più sensibili della popolazione, ossia le donne e i bambini, che nei paesi in via di sviluppo annoverano spesso tra i compiti più gravosi quelli della raccolta della legna e dell'acqua potabile.

Poiché spesso nei paesi meno sviluppati non si ha la presenza di una rete di distribuzione del metano sufficientemente estesa, si rivolge una attenzione particolare all'utilizzo del gas associato sotto forma di gas naturale liquefatto (GNL) e/o di GPL (Gas di Petrolio Liquefatto)[3], o alla sua trasformazione in carburanti liquidi sintetici: lo sviluppo

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[2] Advisory Group on Energy and Climate Change.

[3] Il gas associato è spesso composto in buona parte da etano, propano e idrocarburi più pesanti, e si presta dunque alla separazione di tali componenti al fine di ottenere come prodotti separati GNL e GPL.

di programmi di distribuzione su larga scala in Brasile e Senegal ha infatti dimostrato la fattibilità della distribuzione di tali combustibili in aree rurali, evidenziando anche la conseguente creazione di nuovi posti di lavoro.

Gli stakeholder e il ruolo della Banca Mondiale

Nonostante le evidenti ripercussioni negative che caratterizzano la pratica del gas flaring, questa è ancora ampiamente utilizzata soprattutto a causa del fatto che una soluzione del problema è molto complessa, anche perché quasi sempre comporta il coinvolgimento di diversi stakeholder, ognuno dei quali caratterizzato da un diverso interesse riguardo al problema.

In particolare, essi possono essere suddivisi in quattro macro-categorie:

- i **produttori**, che di norma sono interessati a recuperare il gas associato solo nel caso in cui questa operazione assicuri loro un vantaggio economico;
- i **governi locali**, che dovrebbero occuparsi di contrastare il fenomeno definendo una legislazione chiara e promuovendo la commercializzazione del gas, eventualmente occupandosi di rimuovere o limitare i vincoli che la contrastano, e dovrebbero inoltre assumere un ruolo di coordinamento degli altri soggetti coinvolti;
- i **consumatori privati e industriali** e i **gestori delle infrastrutture** di distribuzione del gas, che dovrebbero essere disposti a stipulare accordi particolari, come ad esempio i contratti *take or pay*, al fine di garantire il ritiro e la distribuzione regolare del gas recuperato, rendendone il consumo prioritario rispetto a quello di altri combustibili;
- le **organizzazioni internazionali**, che possono essere un valido supporto per i governi locali, sopratutto nel caso in cui essi non siano dotati delle conoscenze tecniche necessarie a risolvere il problema con le modalità adeguate o del denaro da investire in progetti di riduzione del gas flaring.

Tre le organizzazioni internazionali che si occupando della riduzione del gas flaring, la più importante è sicuramente la Banca Mondiale, che ha dedicato al problema l'iniziativa GGFR (Global Gas Flaring Reduction): tale iniziativa ha come scopo principale lo sfruttamento dei meccanismi definiti dal protocollo di Kyoto (*Clean Development Mechanisms*, *Joint Implementation* e *Emission Trading*) al fine di supportare investimenti volti al recupero del gas associato, dimostrando l'effettiva applicabilità di questi meccanismi al particolare contesto.

Impianti e principali tecnologie utilizzabili per la riduzione del gas flaring

Impianti e processi comuni

Indipendentemente dalla tecnologia utilizzata come alternativa al flaring, tipicamente gli impianti che trattano gas associato hanno alcune caratteristiche che si traducono in impianti e in processi comuni a tutti: principalmente si tratta di impianti per l'eventuale trattamento del gas e di infrastrutture per il trasporto del gas dal pozzo all'impianto vero e proprio.

Le infrastrutture preposte al trasporto del gas associato sono *pipeline* che raccolgono tramite rami secondari i vari flussi di gas provenienti dai pozzi e lo convogliano in un ramo principale, che giunge poi all'impianto di trattamento finale.

Questo tipo di pipeline è differente da quello comunemente utilizzato per i gasdotti in quanto si tratta di un trasporto generalmente in regime bifase (liquido e gas), inoltre il gas trasportato è grezzo, non raffinato e comunque non destinato all'utente finale.

Un primo processo necessario è la separazione del gas dal petrolio al quale è associato e dall'acqua sempre presente in soluzione. La separazione dall'acqua viene effettuata per facilitare i trattamenti chimici e fisici e il successivo trasporto del gas.

Una volta separato, il gas necessita di opportuni trattamenti: infatti il gas separato non è puro, anzi risulta essere ricco di altri composti indesiderati, quindi i principali trattamenti cui va incontro sono trattamenti di rimozione (rimozione di gas acidi, deidratazione, rimozione del mercurio, separazione dall'azoto). A questi si aggiunge spesso un processo di frazionamento, nel quale il metano viene separato dagli altri composti più pesanti. In caso di massiccia presenza di tali composti è possibile commercializzarli separatamente sotto forma di GPL.

Tecnologie alternative

Esistono diverse possibili tecnologie alternative alla combustione in loco del gas associato. Alcune di queste sono ormai consolidate e affidabili, applicate da tempo anche in altri ambiti, mentre altre sono in fase di studio e potrebbero rappresentare valide alternative in un prossimo futuro.

Tra quelle mature le principali sono: re-iniezione del gas nel pozzo, trasporto del gas a una rete o un mercato tramite gasdotti e vendita a utenti finali, liquefazione di gas (produzione di Gas Naturale Liquefatto, GNL), separazione dei composti pesanti e produzione di GPL, generazione elettrica tramite combustione del gas, produzione di altri combustibili tramite processi Gas-To-Liquid.

Ogni tecnologia ha le proprie caratteristiche che la rendono più o meno adeguata al contesto di interesse, tipicamente si possono ricavare degli intervalli di portate per i quali queste tecnologie sono o meno convenienti e implementabili.

Re-iniezione La pressione di un giacimento petrolifero tende a calare durante la vita del pozzo e, conseguentemente, cala anche la produzione di greggio. Per sostenere e incrementare la produzione di petrolio si può cercare di aumentare la pressione del *reservoir* iniettando il gas associato nel pozzo. Questo processo consente di evitare in grossa parte il trattamento del gas associato (non è necessario sottrarre i vari inquinanti) e consente un elevato incremento di produzione di un prodotto pregiato come il petrolio; d'altra parte rappresenta anche uno spreco considerevole di una risorsa altrettanto preziosa come il gas. Inoltre sono necessari ingenti investimenti (si devono perforare pozzi aggiuntivi) e il gas ha bisogno di essere riportato alla pressione adeguata tramite compressori, con conseguente consumo di energia.

Vendita Una seconda possibilità di utilizzo del gas associato è la vendita diretta del gas tal quale (a privati, a industrie o ai mercati). Questa vendita può avvenire sia localmente alla popolazione residente nella zona del pozzo o dell'impianto (il gas può essere utilizzato anche per alimentare un impianto di teleriscaldamento), sia in seguito al trasporto su lunghe distanze. Il trasporto del gas è possibile grazie a una serie di compressori posti in stazioni di compressione lungo tutto il percorso del gasdotto. Questi compressori sono alimentati da turbine a gas o da motori a combustione interna.

Produzione di GNL Il gas trattato può anche essere compresso fino e oltre il suo punto di liquefazione, così da trattare del liquido anziché del gas e da ridurre considerevolmente i volumi da trasportare.

Produzione di GPL Come detto precedentemente è possibile anche frazionare il gas per separare le parti più leggere da quelle condensabili e utilizzarle in maniera differente.

Produzione di potenza Un altro dei possibili utilizzi del gas trattato è la combustione in turbine a gas al fine di produrre energia elettrica. Le configurazioni possibili sono due: ciclo semplice e ciclo combinato, quest'ultimo caratterizzato dal recupero di calore dai gas combusti tramite un ciclo a vapore sottoposto. Eventualmente si può operare l'impianto anche in assetto cogenerativo, ove siano presenti anche utenze termiche.

Processi Gas-To-Liquid Infine sono possibili diversi processi chimici Gas-To-Liquid (il più comune dei quali è il Fischer-Tropsch), per la produzione di combustibili liquidi sintetici quali benzina, gasolio, metanolo.

Un approccio multicriteriale per la riduzione del gas flaring

Metodi decisionali

Come si è già visto fin qui, realizzare un progetto per la riduzione del gas flaring è spesso operazione complicata a causa della presenza di molti vincoli di svariata natura.

Supponendo di aver selezionato alcune possibili alternative impiantistiche sulla base di uno studio di pre-fattibilità tecnica effettuato dai produttori di gas e petrolio coinvolti nel progetto[4], uno dei problemi principali è appunto quello di effettuare una scelta tra queste alternative ponendosi l'obiettivo di selezionare quella che raggiunga nel complesso il miglior grado di sostenibilità.

Considerando che per raggiungere tale obiettivo è necessario analizzare ogni alternativa nei suoi aspetti economici, ambientali e sociali (ossia prestando attenzione alle tre dimensioni di cui si compone la sostenibilità) ed è necessario trovare un accordo tra tutti gli stakeholder coinvolti, una buona soluzione può essere quella di utilizzare un metodo decisionale multicriteriale, cioè un metodo che permetta di trovare la soluzione che rappresenta il miglior compromesso tra diversi criteri di decisione.

Per capire quale tra i vari metodi resi disponibili dalla letteratura sia preferibile utilizzare nel contesto analizzato in questo studio, è necessario evidenziare le caratteristiche principali del problema, tenendo conto del fatto che, come spiegato poi più avanti, sarà necessario utilizzare degli indicatori per analizzare i vari aspetti di ogni alternativa:

- un progetto di riduzione del gas flaring coinvolge diversi stakeholder, ognuno dei quali è caratterizzato da un diverso interesse e da un diverso potere di negoziazione;

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[4] Le diverse alternative possono differire non solo per la tecnologia utilizzata nel processo (ad esempio Gas-To-Liquid piuttosto che GNL), ma anche per la configurazione impiantistica (ad esempio le zone attraversate da pipeline possono essere diverse).

- a causa della difficoltà di ottenere dati quantitativi per valutare alcuni indicatori, alcuni di questi devono essere valutati in maniera qualitativa;
- i vari indicatori devono poter essere adimensionalizzati in quanto sono caratterizzati da unità di misura differenti.

I metodi decisionali si suddividono in due famiglie principali: metodi multi-obiettivo e metodi multi-attributo. I primi ricercano la migliore soluzione di compromesso operando nel continuo, pertanto individuando un punto di ottimo tra infinite soluzioni possibili attraverso l'ottimizzazione di funzioni matematiche, mentre i secondi permettono di ottenere un ordinamento tra un numero finito di diverse alternative. Considerando le caratteristiche del problema, è chiaro che il metodo da utilizzare vada ricercato tra quelli appartenenti alla seconda famiglia.

I diversi metodi multi-attributo si differenziano per quanto riguarda il tipo di approccio al problema e per l'algoritmo di calcolo, ma sono accomunati dal fatto di richiedere la definizione di alcuni parametri fondamentali:

- l'obiettivo della decisione (nello specifico, la riduzione o eliminazione del gas flaring);
- le alternative tra cui scegliere;
- i criteri da usare per analizzare le alternative.

Inoltre, generalmente richiedono di procedere secondo questi passaggi fondamentali:

- definire le matrici di valutazione, ossia matrici ove a ogni alternativa viene assegnato un punteggio confrontandola rispetto alle altre relativamente a ognuno dei criteri considerati nell'analisi;
- normalizzare le matrici;
- definire un peso per ogni criterio utilizzato;
- aggregare i dati provenienti dai confronti relativi ai vari criteri tenendo conto dei pesi dei criteri stessi, in modo da ottenere un ordinamento finale delle alternative;
- realizzare una analisi di sensitività per verificare la stabilità della soluzione.

Una analisi dei diversi metodi multi-attributo, tenendo conto delle caratteristiche peculiari di un progetto di riduzione del gas flaring, ha portato alla scelta del metodo AHP (Analytic Hierarchy Process, ideato da T. Saaty), in quanto questo metodo permette l'utilizzo simultaneo di indicatori di tipo qualitativo e quantitativo e prevede la scomposizione del problema analizzato in diversi livelli gerarchici, operazione che è certamente adatta a questo contesto.

Il metodo si compone delle seguenti fasi principali:

1. **Scomposizione gerarchica del problema** In questa prima fase si definiscono l'obiettivo generale, i criteri per raggiungere tale obiettivo (ed eventuali sotto-criteri) e le alternative tra le quali bisogna effettuare la scelta. Questi elementi vengono ordinati secondo una gerarchia piramidale in base al grado di dettaglio (al vertice l'obiettivo principale, mentre alla base i criteri più specifici e le alternative). Pertanto, ogni livello della gerarchia è dipendente dal livello superiore, mentre gli elementi di uno stesso livello sono indipendenti tra loro. Nello strutturare la gerarchia il numero di livelli dipende dalla complessità del problema e dal livello di dettaglio che l'analisi richiede per risolverlo. In ogni caso, questa dovrebbe essere composta dai seguenti elementi principali:

   (a) obiettivo generale ed eventuali sotto-obiettivi;
   (b) criteri che soddisfano l'obiettivo generale o i sotto-obiettivi;
   (c) i sotto-criteri di ciascun criterio;
   (d) i decisori coinvolti, considerando i loro obiettivi e diversi poteri di negoziazione;
   (e) le alternative.

2. **Assegnazione di un punteggio ad ogni alternativa sulla base di un confronto a coppie** Per stabilire le priorità tra i vari elementi di ciascun livello della gerarchia si utilizza la tecnica del confronto a coppie: gli elementi di un livello vengono confrontati a due a due rispetto a ogni elemento posto al livello superiore (i criteri vengono confrontati tra loro in riferimento all'obiettivo generale, i sotto-criteri in riferimento al relativo criterio e infine le alternative rispetto ai sotto-criteri). Da questo confronto si può stabilire il grado di importanza di un elemento rispetto a un altro, entrambi appartenenti allo stesso livello. Il risultato del confronto è un coefficiente a_{ij}, detto coefficiente di dominanza, che rappresenta una stima della dominanza dell'elemento i rispetto all'elemento j. Per determinare i valori dei coefficienti si utilizza la scala di Saaty: tale scala è basata su numeri da 1 a 9, dove 1 indica che l'elemento i ha la stessa importanza dell'elemento j, mentre 9 indica che l'elemento i è estremamente più importante di j. I coefficienti di dominanza definiscono una matrice quadrata $n \times n$ detta matrice dei confronti a coppie:

   $$[\mathbf{A}] = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix}$$

   La matrice risulta essere simmetrica e reciproca. La scala di Saaty può essere usata direttamente dal decisore per effettuare un confronto di tipo qualitativo. Tuttavia, nel caso in cui un criterio possa essere valutato per mezzo di un indicatore di tipo quantitativo, i valori che tale indicatore assume relativamente alle varie alternative possono essere rinormalizzati tra 1 e 9 e successivamente inseriti nella matrice.

3. **Aggregazione dei risultati parziali** I valori contenuti nelle matrici dei confronti a coppie sono utilizzati per derivare l'ordine delle priorità tra gli elementi di ciascuna matrice, ossia un vettore di pesi che esprime la prestazione finale delle alternative confrontate rispetto al criterio di riferimento. La scala delle priorità è un vettore che esprime per ogni riga le priorità fra gli elementi. In particolare, questo vettore è l'*autovettore principale* della matrice dei confronti a coppie. Per evitare il calcolo dell'autovettore si può utilizzare il metodo approssimato della media geometrica: l'operazione prevede l'estrazione dalla matrice $[\mathbf{A}]$ della radice n-esima dei prodotti degli n elementi di ciascuna riga, ottenendo il vettore delle priorità $\mathbf{w}$ di componenti w_i. Successivamente, il vettore viene normalizzato dividendo ogni componente di $\mathbf{w}$ per la somma di tutte le sue componenti w_i. Il vettore $\mathbf{w}$ normalizzato esprime la priorità locale di ogni elemento rispetto all'elemento posto al livello superiore. Per ottenere un ordinamento globale delle alternative rispetto all'obiettivo finale, si procede con l'aggregazione e il confronto dei criteri posti ai livelli superiori. L'ordinamento globale risulta pertanto dalla somma pesata tra i punteggi attribuiti a ciascuna alternativa (indicanti il grado di preferenza di una rispetto a un'altra) e i pesi attribuiti ai criteri e ai sotto-criteri. I pesi globali rappresentano il risultato

finale della valutazione: un'alternativa sarà tanto più preferibile quanto maggiore è il suo peso globale.

4. **Test di consistenza** Questo test permette di verificare che le matrici dei confronti a coppie siano state riempite in modo coerente e accurato. In particolare, i confronti a coppie devono essere effettuati senza violare il principio di transitività:

$$se\, A > B\, e\, B > C \Longrightarrow A \gg C$$

Il test si effettua mediante il calcolo del cosiddetto *Consistency Ratio* (*Rapporto di Consistenza*): se *CR* risulta essere inferiore a $0,10$ si può ritenere che i confronti siano stati effettuati correttamente, mentre se ciò non è verificato è necessario ricontrollare i valori inseriti nella matrice.

5. **Analisi di sensitività** L'analisi di sensitività permette di verificare la stabilità dei risultati ottenuti. Possono essere effettuate diverse simulazioni, variando i pesi assegnati a ogni criterio e sotto-criterio o pesi assegnati ai diversi decisori e formulando diversi scenari "what-if" per verificare la presenza di un elemento gerarchico caratterizzato da una eccessiva influenza sul risultato finale in maniera tale per cui una piccola perturbazione delle condizioni iniziali porti a una soluzione radicalmente differente.

6. **Discussione dei risultati tra i vari decisori** I risultati dell'analisi dovrebbero essere discussi e analizzati dai vari decisori in modo da effettuare una approfondita valutazione critica prima di procedere alla scelta definitiva di una alternativa.

Limiti del modello Il modello AHP è caratterizzato da alcuni limiti noti.

Innanzitutto la procedura in sé stessa è molto lunga, e il numero di confronti a coppie da effettuare cresce esponenzialmente al crescere del numero di alternative e criteri.

Per quanto riguarda l'algoritmo, un punto critico riguarda l'operazione di normalizzazione degli indicatori qualitativi: una volta effettuata tale operazione, le distanze assolute tra i valori assunti dai vari indicatori non vengono preservate, e ciò potrebbe portare in alcuni casi ad ottenere una soluzione non affidabile.

Infine, il limite più critico è legato al fatto che si può manifestare il cosiddetto *rank reversal*: in alcuni casi particolari l'aggiunta o la rimozione di una alternativa può causare uno scambio di ordinamento tra due o più altre alternative. Il fenomeno può manifestarsi anche nel caso in cui venga aggiunta o eliminata una alternativa che non dovrebbe influenzare l'ordinamento delle altre, come ad esempio nel caso in cui venga aggiunta una alternativa che presenta valori degli indicatori peggiori rispetto a tutti i criteri. La probabilità che si verifichi una situazione di *rank reversal* cresce al crescere del numero di alternative ed è maggiore nel caso in cui siano presenti alternative molto simili tra loro.

Nonostante queste limitazioni, il modello risulta comunque particolarmente adatto per un utilizzo nel contesto d'interesse di questo lavoro, come è spiegato più avanti in modo più dettagliato.

Indicatori fondamentali per la riduzione del gas flaring

In riferimento ai difetti del modello AHP, nel caso di un progetto di riduzione del gas flaring si possono effettuare le seguenti considerazioni: riguardo il primo problema (la notevole lunghezza nell'utilizzo e applicazione del metodo), considerando la tipologia del problema e i soggetti coinvolti altre fasi del progetto saranno sicuramente molto più laboriose della compilazione delle matrici.

Relativamente ai problemi legati alla dipendenza della decisione da parametri soggettivi, questi possono essere tenuti sotto controllo confidando nella serietà dei decisori e nel loro gran numero, che dovrebbe limitare l'impatto della valutazione del singolo decisore.

Per quanto riguarda poi la perdita di informazioni dovuta alla normalizzazione dei dati, il fatto è stato mitigato in questo lavoro introducendo un ulteriore confronto qualitativo tra i valori estremi assunti dalle alternative per ogni indicatore e scegliendo di conseguenza un valore massimo per effettuare la normalizzazione compreso tra 1 e 9.

Infine la situazione di *rank reversal* si dovrebbe avere solo tra soluzioni con punteggi vicini, così vicini che la loro differenza non dovrebbe essere considerata rilevante poiché superiore all'incertezza dovuta alle misurazioni e alle stime degli indicatori e all'incertezza introdotta con i confronti a coppie qualitativi.

Queste considerazioni portano alla conclusione che l'utilizzo del modello AHP in questo contesto sia giustificato dal fatto che mentre gli svantaggi risultano mitigati, i vantaggi sono invece inalterati.

Volendo dunque procedere all'implementazione del metodo riferendosi al caso particolare di progetti per la riduzione del gas flaring, la struttura gerarchica è definita come di seguito: al vertice della gerarchia è posto l'obiettivo finale, quindi la riduzione (o l'eliminazione) del gas flaring. Inoltre, dovendo la soluzione al flaring essere il più possibile sostenibile, al primo livello della gerarchia sono collocate le tre dimensioni della sostenibilità (Economica, Ambientale e Sociale), che saranno quindi i tre criteri di primo livello. Ciascuno di questi criteri deve essere valutato utilizzando dei sotto-criteri (criteri di secondo livello) più specifici, in modo da avere alla base della gerarchia degli elementi semplici da valutare e utilizzare per il confronto. Ognuno di questi sotto-criteri permette una valutazione di ogni alternativa per mezzo di uno o più indicatori di tipo qualitativo o quantitativo.

La scelta di questo sistema gerarchico è basata su indicazioni date nell'ambito della sostenibilità da organismi internazionali (come le Nazioni Unite) e di specificità emerse in precedenti studi nell'ambito del gas flaring.

Di seguito sono elencati i sotto-criteri considerati, ciascuno riferito alla rispettiva dimensione di appartenenza.

Economica: fattibilità e convenienza economica, in particolare dal punto di vista del finanziatore.

Ambientale: utilizzo di suolo, aria e acqua, livello di rumore, impatti sul territorio a breve e lungo termine.

Sociale: occupazione diretta e indiretta, accesso all'energia considerando elettricità, energia termica e combustibili, impatto sulla salute.

Una volta scelti i criteri da valutare è opportuno selezionare un set di indicatori utilizzabili. Tali indicatori devono risultare rilevanti rispetto al criterio da valutare,. Inoltre deve sussistere la possibilità di calcolarli o valutarli in maniera semplice e poco onerosa (sia in termini di tempo sia di altre risorse). Poiché non tutti gli indicatori possono essere ricondotti a dei valori numerici calcolati o misurati, almeno nella fase di pre-fattibilità in cui il metodo dovrebbe essere utilizzato, è opportuno notare che alcuni indicatori saranno di tipo quantitativo mentre altri dovranno essere di tipo qualitativo.

Indicatori della dimensione Economica Gli indicatori della dimensione Economica utilizzati nel metodo proposto in questo lavoro sono stati selezionati tra quelli che tipicamente valutano la redditività di un investimento; in particolare sono stati selezionati il tasso interno di rendimento (Internal Rate of Return, IRR), il tempo di rientro dall'investimento (Pay-Back Time, PBT) e il valore netto attualizzato dell'investimento (Net Present Value, NPV). Ognuno di questi indicatori (tutti quantitativi) ha caratteristiche e significati diversi, e ovviamente un diversa procedura di calcolo, è dunque possibile che non tutti gli indicatori siano disponibili, anche in base alla politica di scelta dell'azienda che si occupa del progetto o del committente; nel metodo proposto è quindi possibile utilizzarne solo alcuni di questi tre.

Indicatori della dimensione Ambientale Gli indicatori selezionati per la valutazione della dimensione ambientale sono i seguenti:

- **Consumo di suolo** (quantitativo), inteso come occupazione fisica di terreno da parte di edifici, strutture o condotte, indipendentemente dal tipo di terreno occupato o attraversato.
- **Consumo di acqua**(quantitativo), inteso come utilizzo di acqua sottratta all'ambiente che non viene poi restituita ad esso se non in condizioni fortemente differenti (particolarmente in termini di composizione e inquinanti).
- **Inquinamento dell'aria,** sia a livello globale sia a livello locale. Risulta dalla aggregazione di sotto-indicatori che misurano le emissioni di CO_2 (quantitativo, inquinamento globale), di NO_x e di SO_x (quantitativi, inquinamento locale).
- **Livello di rumore** (qualitativo), inteso come differenza, rispetto alla situazione precedente l'intervento, del livello di rumore percepito dalla popolazione che abita nelle vicinanze dell'impianto di trattamento del gas associato. Dipende quindi dalla distanza delle abitazioni dall'impianto, nonché dalla quantità di persone che vi abitano vicino.
- **Impatto durante la costruzione** (qualitativo), che misura quindi gli effetti transitori e temporanei dovuti alla costruzione degli edifici e delle infrastrutture.
- **Impatto sull'ecosistema** (qualitativo), che tiene conto del differente valore dell'ecosistema interessato dalla presenza dell'impianto o dalle condotte per il trasporto del gas.

Indicatori della dimensione Sociale Gli indicatori selezionati sono i seguenti:

- **Numero di nuove assunzioni** (quantitativo), misura esclusivamente l'impatto diretto sull'occupazione della popolazione locale.
- **Altri impatti locali** (qualitativo), utilizzato solo se ci sono impatti indiretti sull'occupazione locale dovuti a un indotto creato dall'impianto.
- **Aumento delle connessioni elettriche** (quantitativo), valuta l'accesso all'energia (elettrica) aggiuntivo consentito dal nuovo impianto, considerando sia nuove connessioni sia miglioramenti della fornitura.
- **Aumento delle connessioni di energia termica** (quantitativo), analogo al precedente, valutato sull'energia termica. La sostituzione di altri sistemi di produzione di calore ha effetti anche sull'*Inquinamento dell'aria* e sull'*Impatto sulla salute.*

- **Distribuzione locale di combustibili,** valutato con tre sotto-indicatori (quantitativi) che considerano separatamente le connessioni a una rete di gas naturale, la distribuzione di GPL o altri combustibili da GTL, la distribuzione di GNL.
- **Impatto sulla salute** (qualitativo), considera la variazione delle condizioni di salute dovute alla presenza dell'impianto valutato.

Una volta definiti i criteri e gli indicatori fondamentali bisogna implementare il modello AHP riferendosi al problema di riduzione del gas flaring: ciascun criterio e indicatore va inserito nell'opportuno livello della gerarchia rispettando le relazioni appena spiegate.

In seguito bisogna effettuare una serie di confronti a coppie tra criteri e indicatori per stabilire i vettori di priorità relativi. Essenzialmente ci sono due tipi di confronti da effettuare e di matrici da compilare:

- il primo tipo di confronto avviene tra le alternative considerando un singolo indicatore come termine di paragone:

Indicatore	Alternativa 1	Alternativa 2	Alternativa 3	$\mathbf{x_{ind}}$
Alternativa 1	1 vs 1	1 vs 2	1 vs 3	x_{ind1}
Alternativa 2	2 vs 1	2 vs 2	2 vs 3	x_{ind2}
Alternativa 3	3 vs 1	3 vs 2	3 vs 3	x_{ind3}

- il secondo tipo di confronto avviene tra gli indicatori (o i criteri), considerando come termine di paragone il criterio di livello superiore a cui si riferiscono:

Criterio	Indicatore 1	Indicatore 2	Indicatore 3	$\mathbf{x_{crit}}$
Indicatore 1	1 vs 1	1 vs 2	1 vs 3	x_{crit1}
Indicatore 2	2 vs 1	2 vs 2	2 vs 3	x_{crit2}
Indicatore 3	3 vs 1	3 vs 2	3 vs 3	x_{crit3}

I vettori delle priorità ottenuti vengono poi combinati per ottenere il vettore di priorità globale che determina l'ordine di preferenza e il punteggio da assegnare a ciascuna alternativa analizzata.

Per poter applicare il modello a un caso reale senza utilizzare software commerciali è stato sviluppato un modello basato su *Excel*, che consente di confrontare fino a 10 alternative scegliendo sia quali criteri utilizzare sia stabilendo l'importanza dei criteri mediante confronti a coppie. Oltre a fornire il risultato finale il programma consente anche di visualizzare a struttura del punteggio di ciascuna alternativa, mettendo in luce punti di forza e punti di debolezza. Per la verifica dell'algoritmo è stato operato un confronto tra alcuni risultati ottenuti con *Excel* e quelli ottenuti con il software *Super Decision*, che ha confermato la bontà della procedura implementata in *Excel.* Inoltre il software *Super Decision* ha permesso di compiere un'analisi di sensitività delle soluzioni trovate.

Russia: il caso-studio

Il modello presentato in precedenza è stato applicato un caso di studio grazie a una collaborazione con l'azienda *Techint E&C s.p.a.*

La collaborazione ha permesso di raccogliere una serie di dati e informazioni su un progetto commissionato da una delle maggiori compagnie petrolifere operanti in Russia. Il progetto prevede il recupero di gas associato proveniente da diversi campi nella regione siberiana (attualmente destinato a essere bruciato in torcia) e il suo utilizzo in maniera alternativa. I campi interessati appartengono a differenti proprietari, quindi gli stakeholder coinvolti sono numerosi. Il compito di *Techint* è quello di definire quale alternativa d'impianto e di utilizzo del gas sia la migliore. Dopo uno studio preliminare riguardante le diverse possibilità di utilizzo del gas e del diverso modo di trasportare il gas dai campi al luogo dell'impianto, sono state selezionate 4 alternative possibili da confrontare tra di loro.

Le prime due alternative (denominate B1 e B2) prevedono di situare l'impianto principale nei pressi di una città situata a circa $600km$ di distanza dai campi. Le due alternative di differenziano per il diverso grado di separazione del gas associato, poi comunque destinato alla vendita: nel primo caso si ha una separazione tra gas naturale (metano e etano) e idrocarburi più pesanti, nel secondo si ottiene una separazione più spinta dividendo tutti i componenti fino al butano, ottenendo quindi un prodotto maggiormente valorizzato ma con costi d'impianto ovviamente maggiori. L'impianto dovrebbe essere realizzato completamente ex-novo poiché non sono presenti altre infrastrutture o edifici utilizzabili.

Le altre due alternative (T1 e T2) prevedono invece il trattamento del gas associato (e la sua separazione tra gas naturale e frazioni più pesanti) in un impianto chimico già esistente nei pressi di una seconda città. Sfruttando l'impianto esistente si avrebbero alcuni risparmi sull'investimento e una parte del prodotto potrebbe essere utilizzata nell'impianto stesso come materia prima, che altrimenti deve essere acquistata da altri fornitori, mentre la rimanente parte del gas verrebbe comunque venduta. Lo svantaggio delle alternative T1 e T2 consiste nella maggior distanza dai campi (circa $800km$) con conseguenti maggiori costi di investimento per la pipeline. T1 e T2 si differenziano per il fatto di utilizzare o meno il calore dei gas di scarico delle turbine presenti nell'impianto, che può essere sfruttato dal sistema di teleriscaldamento già presente nella città.

Il modello AHP è quindi stato applicato al progetto di *Techint* attivando gli opportuni indicatori, utilizzando i dati numerici forniti dall'azienda e realizzando i dovuti confronti a coppie per quanto riguarda gli indicatori qualitativi e i vari elementi della gerarchia utilizzando informazioni di tipo qualitativo riferite al contesto in esame.

Il risultato finale dell'applicazione del modello restituisce un ordinamento finale tra le alternative differente da quello realizzato da *Techint*, e di conseguenza l'alternativa migliore suggerita dal modello (T2) non è la stessa scelta in seguito allo studio dell'azienda (T1).

Il motivo di questa differenza è il diverso criterio utilizzato per la scelta: in particolare *Techint* ha basato la scelta dell'alternativa migliore unicamente su parametri di prestazioni economica (IRR) scelti dal cliente, che non premiano il teleriscaldamento per la scarsa remunerazione del calore venduto.

L'analisi di sensitività che ha seguito l'applicazione del modello evidenzia la stabilità della soluzione finale, fatto che dovrebbe garantire l'affidabilità del risultato anche al variare, in maniera limitata, dei giudizi dei decisori relativamente ai confronti a coppie.

Conclusioni

Conclusioni generali

Il modello AHP che è stato implementato si basa sulla definizione di una gerarchia che caratterizzi il problema, utilizzando una serie di criteri e indicatori al fine di scegliere la migliore tra un certo numero di alternative per ridurre o eliminare il gas flaring. I confronti tra le alternative, così come la definizione dei pesi dei vari elementi all'interno della gerarchia, si basano su dei confronti a coppie tra i vari elementi (quantitativi o qualitativi) ottenuti utilizzando la scala di Saaty. Per ottenere il risultato finale è necessario combinare tutti i pesi ottenuti seguendo la struttura gerarchica precedentemente definita: l'alternativa migliore è quella che ottiene il punteggio più alto.

Al fine di validare il risultato e poterlo considerare affidabile per la decisione finale si ribadisce innanzitutto l'importanza di un'analisi di sensitività, che permette di assicurarsi che l'algoritmo non dia luogo a una soluzione molto differente in seguito a una piccola variazione delle condizioni iniziali (ossia dei giudizi qualitativi sui pesi degli elementi e sulle prestazioni delle alternative).

Il modello AHP presenta alcuni punti di forza che lo rendono particolarmente adatto per la valutazione e l'ordinamento delle diverse alternative che possono essere proposte al fine di ridurre il gas flaring. In particolare, i principali vantaggi sono:

- scomposizione gerarchica del problema in elementi più semplici da valutare;
- possibilità di utilizzare sia indicatori quantitativi sia indicatori qualitativi;
- partecipazione di più decisori (stakeholder) al processo decisionale;
- i confronti a coppie tra i vari elementi della gerarchia rendono più semplice il processo rispetto a un metodo che richieda valutazioni globali.

Tra tutti questi punti di forza si vuole soprattutto sottolineare il fatto che sia possibile effettuare una scelta coinvolgendo vari stakeholder, i quali possono contribuire alla definizione dei pesi di tutti gli elementi della gerarchia e alla valutazione delle prestazioni delle differenti alternative secondo i vari criteri.

Il modello, chiaramente, presenta anche dei punti deboli, il più importante dei quali è il possibile insorgere del cosiddetto *rank reversal*, ovverosia di un'inversione dell'ordinamento delle alternative; questo problema si dovrebbe manifestare però solo in particolari condizioni, dalle quali è bene tenersi il più lontano possibile, e può comunque essere controllato effettuando un'attenta valutazione della soluzione data dall'algoritmo.

Anche la soggettività dei decisori influisce ovviamente sul risultato finale, e potrebbe perciò da un certo punto di vista essere annoverata tra i difetti del modello, tuttavia questo è un aspetto intrinseco (e non necessariamente negativo) comune a tutti i processi decisionali.

Sviluppi futuri

Diversi sviluppi del presente lavoro sono possibili.

In particolare, una prima possibilità riguarda l'applicazione del modello a dei casi reali per verificarne l'affidabilità e per controllare la pertinenza dei criteri e degli indicatori utilizzati, eventualmente aggiungendone di nuovi o escludendo alcuni di quelli proposti in questo lavoro.

Una seconda analisi che potrebbe completare questo lavoro riguarda invece la verifica dell'efficacia del metodo AHP rispetto ad altri metodi decisionali per valutare le alternative nel contesto di riduzione del gas flaring.

Part I

Gas flaring: impact assessment and technological analysis

Chapter 1

From a problem to an opportunity

1.1 Gas flaring in a global context

With the expression *gas flaring* an open-air burning of natural gases is intended: a pipe, or flare stack, carries gases to the top of a vertical stack, where an ignition system is located.

Facilities in the oil & gas industry can recur this practice because of different reasons. In certain cases flaring is intended as an important safety measure, especially during non-routine occurrences like emergencies, routine failures and so on, or during drilling operations. In these cases the practice avoids hazards to workers and nearby residents.

Other times, after drilling a well, it is necessary to flare gas for a short period, in order to analyse the chemical composition and detect the optimal flow rate, or to dispose of gases contaminated with drilling fluids.

Nevertheless, in most cases gases are burned because of the absence of a recovering system because of various reasons (technical, economic, ...).

Gas flaring represents an alternative to venting gas, a practice that consists in a direct release of gases in the atmosphere: burning the gas have a minor environmental impact since methane has a global warming potential [1] equal to 25 on a mass basis, while the global warming potential of CO_2 is equal to 1 [2].

The most important flaring or venting cause is the existence of the so-called *Associated Petroleum Gas* (APG). There are two types of associated gas: cap gas and solution gas. Cap gas occurs when some gas is stored at the top of an oil deposit. Solution gas is dissolved in the oil. In both situations associated gas is often considered as a by-product and is seen more as a problem than a resource to take advantage of.

According to K. Petrosyan and her study [3], there are three main groups of constraints on associated gas utilisation: market, company and technical constraints.

Market constraints

- Absence of a local market, due to low energy consumptions and/or to market saturated by other fuels. In this case efforts of government for creating or supporting markets are essential

- Uncompetitive downstream energy markets, often linked to government regulation of prices

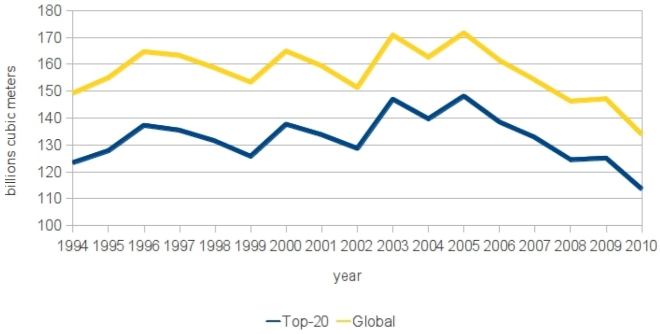

Figure 1.1: Global and Top-20 gas flaring trends (data source: NOAA)

- Prohibitive costs of connections between production areas and consumption areas

Company constraints

- Lack of experience in dealing with associated gas and poor information about innovative technologies
- Opportunity of investments more remunerative than flaring reduction projects

Technical constraints

- Gas flow rate too low for utilisation
- Very unstable gas flow rate
- Excessive contents of sulphur and/or liquids

Another constraint can be the distance between the oil wells and the gas transportation pipeline, with the necessity of significant investment. As a matter of fact, the construction of an additional gas pipeline parallel to the existing oil one would be necessary and this is generally uneconomic. Current troubles with multiphase transportation of oil and gas make the use of this solution very difficult on long distances, so that it is used only in particular condition when other solutions are not possible (e.g. in the case of off-shore platforms).

1.1.1 Flaring gas, wasting energy

NOAA[1] has been estimating national and global gas flaring volumes since 1994 by analysing satellite observations. According to their data, associated gas flaring represents an enormous waste of energy: globally 134 billion m^3 of gas were flared in 2010 (table 1.1).

The analysis of flared gas volumes trends through years from 1994 to 2010 points out that the entity of the problem worldwide is decreasing (figure 1.1)[2]. The global per cent reduction is about 10% in the considered time lag.

Top-20 countries reduced flared volumes on the average, but some countries increased it. To give an example, Iraq gas volumes had a rise of 222% (figure 1.2).

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[1] National Oceanic and Atmospheric Administration.

[2] The complete historical series of data is shown in Appendix A.

Table 1.1: Flared gas in 2010 (data source: NOAA)

Country	Billions m^3
Russia	35.24
Nigeria	15.18
Iran	11.27
Iraq	9.13
Algeria	5.40
Angola	4.08
Kazakhstan	3.80
Libya	3.79
Saudi Arabia	3.36
Venezuela	2.83
Mexico	2.50
Indonesia	2.27
China	2.11
Canada	2.07
USA	2.06
Uzbekistan	1.87
Qatar	1.85
Oman	1.77
Kuwait	1.49
Malaysia	1.47
Top-20	113.54
World	133.90

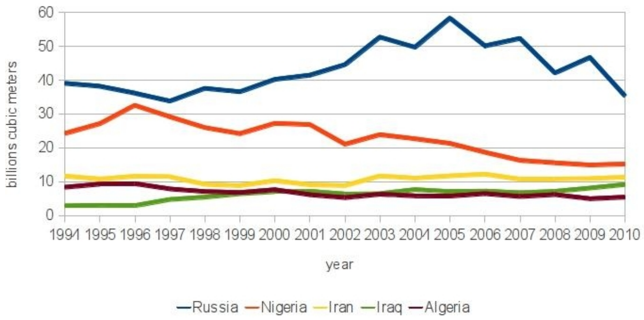

Figure 1.2: Top-5 gas flaring trend (data source: NOAA)

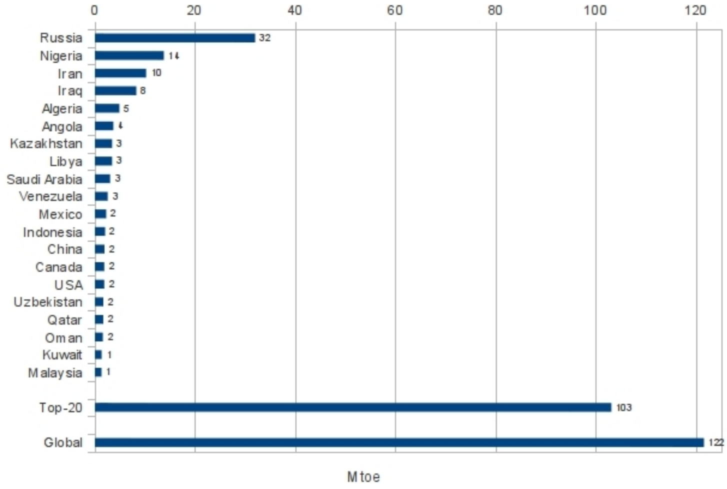

Figure 1.3: Flared gas as primary energy waste. Conversion based on a LHV=38MJ/m^3 (data source: NOAA)

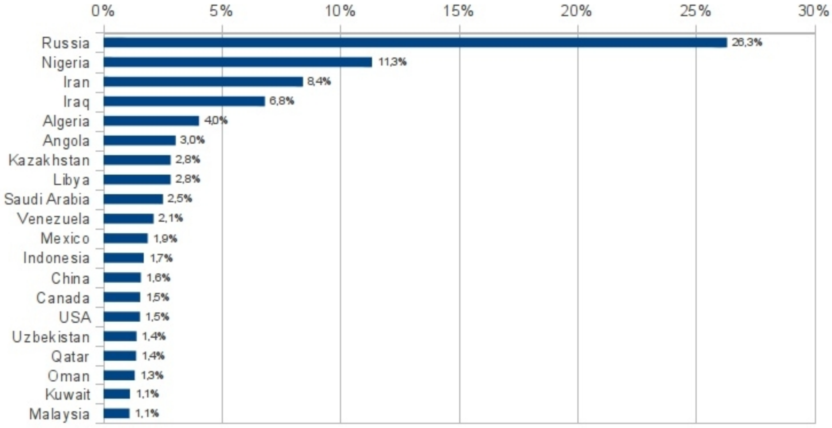

Figure 1.4: Share of flared gas by country, 2010 (data source: NOAA)

In any case, it is evident that the objective of zero gas flaring is still far away.

In addition to this, there are enormous volumes of vented gas. Nevertheless, since a reliable estimation of vented gas is quite impossible because venting is not detectable by satellites[3], data about venting are excluded from this analysis.

The waste of energy associated to gas flaring assuming a LHV of 38MJ/m^3 is shown in figure 1.3.

In table 1.1 it is also shown that gas flaring mostly occurs in developing countries where oil production is relevant.

Nearly all gas flaring occurs in only twenty countries (85%), and top-five countries burn more than 55% (figure 1.4).

Weight of Russia and Nigeria is very relevant: their contribution to global gas flaring is about 37%.

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[3] The only estimations available are provided by oil companies.

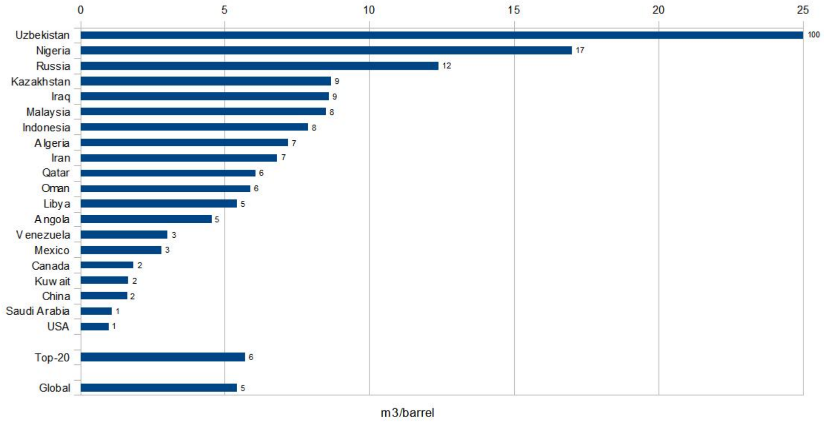

Figure 1.5: Country, Top-20 and global Flared Gas to Oil Ratio (data source: NOAA and EIA)

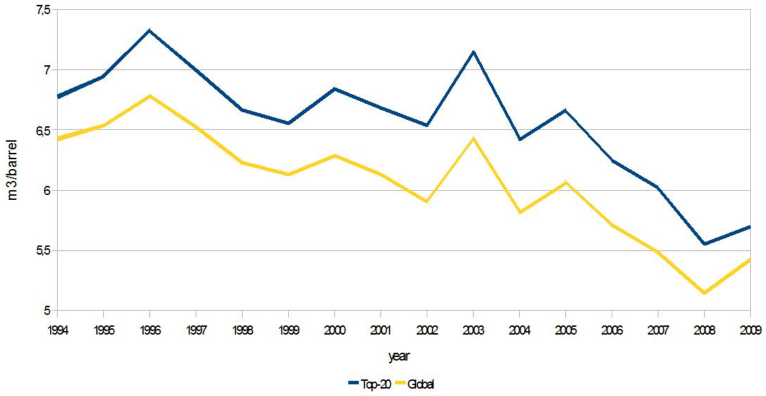

Figure 1.6: Global and Top-20 Flared Gas to Oil Ratio trends (data source: NOAA)

In order to make other considerations, once collected required data, the Flared Gas to Oil Ratio (FGOR) may be defined:

$$FGOR = \frac{m^3_{FG}}{barrel_{oil}} \tag{1.1}$$

FGOR shows how much associated petroleum gas is flared in comparison to how many oil barrels are produced in a country (figure 1.5). Smaller values indicate better performances.

Uzbekistan has the worst value: a FGOR of $100m^3/barrel$ makes this country an outlayer in the list (in figure 1.5 the axis has been cut off). Excluding Uzbekistan, Nigeria and Russia are at the top of the diagram, respectively with an FGOR of $17m^3/barrel$ and $12m^3/barrel$. Both countries performances are widely over Top-20 average, that presents a value of $6m^3/barrel$. At the contrary, Saudi Arabia is one of the most efficient oil producers in the world in terms of gas flaring ($1m^3/barrel$). In the world the mean value is $5m^3/barrel$.

Also the performances in terms of FGOR have improved in recent years, with a global

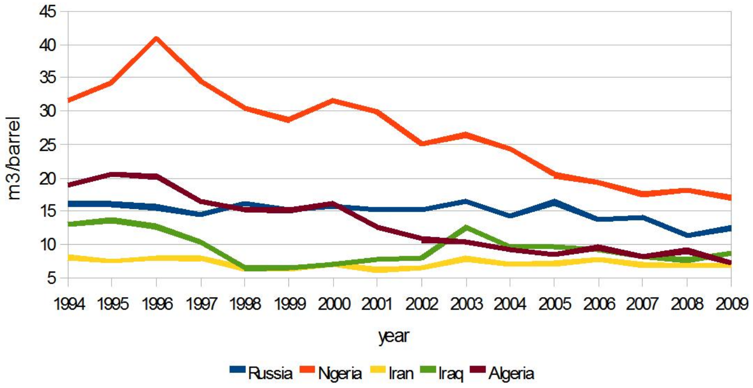

Figure 1.7: Top-5 Flared Gas to Oil Ratio trend (data source: NOAA)

decrement of about 15 percent points in terms of cubic meters of gas per each oil barrel (figure 1.6).

Nigeria and Algeria obtained best results among Top-5 countries (figure 1.7).

FGOR depends not only from the presence or absence of a recovery gas system but also from the quantity of associated gas contained in the oilfield. The associated gas content is identified by the *Gas to Oil Ratio* (GOR):

$$GOR = \frac{m^3_{AG}}{barrel_{oil}} \tag{1.2}$$

Hence, an idea of the efficacy in associated gas recovery is given by FAG index (Flared over Associated Gas) that is the result of a comparison between FGOR and GOR:

$$FAG = \frac{FGOR}{GOR} = \frac{m^3_{FG}}{m^3_{AG}} \tag{1.3}$$

In some countries like Iraq, Angola and Nigeria, flared gas volumes are a significant quota of their total gross natural gas production (figure 1.8).

In the same countries the energy waste due to gas flaring is also a significant quota of the total energy production and the TPES (figures 1.9 and 1.10).

In order to make numbers more handy it is possible, for example, to evaluate a theoretical number of equivalent power plants, i.e. the number of power plants that can be fed by the amount of gas actually flared, considering them the best in class technology as an alternative to gas flaring.

Two options are considered:

1. **Combined cycle power plants**, which represent the state of the art, are considered in a hypothetical top-efficiency scenario, that can be a realistic situation in developed countries.

2. **Simple turbo-gas power plants** are considered in a scenario that represents a more realistic situation for developing countries.

Table 1.2 shows values obtained employing the following hypotheses[4]:

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[4] Data from ENEL Altomonte's plant.

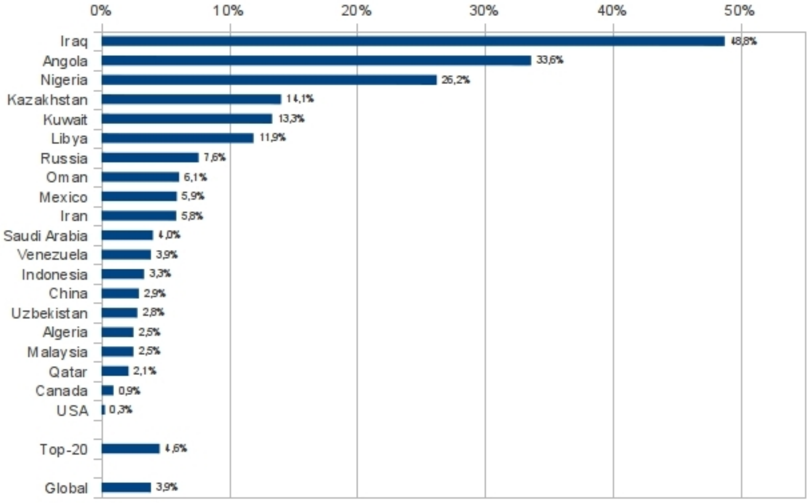

Figure 1.8: Share of flared gas of total gross natural gas production (data source: NOAA and EIA)

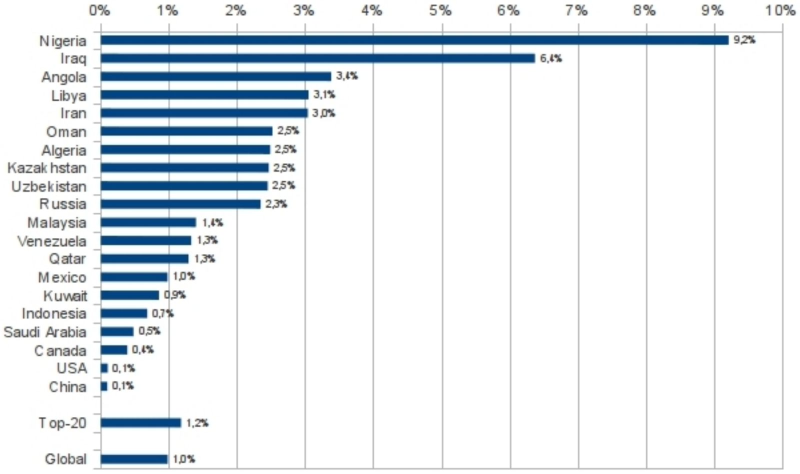

Figure 1.9: Gas flaring compared with total energy production (LHV=38MJ/m^3; data source: NOAA and EIA)

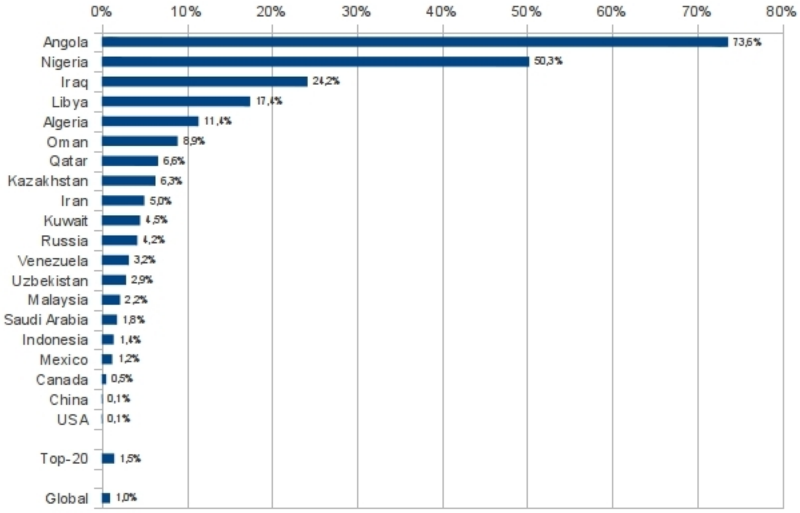

Figure 1.10: Gas flaring compared with TPES (LHV=38MJ/m^3; data source: NOAA and EIA)

Table 1.2: Number of equivalent Simple and Combined Cycle Gas Turbines (calculation based on NOAA's data)

Country	SCGT	CCGT
Russia	70	35
Nigeria	30	15
Iran	22	11
Iraq	18	9
Algeria	11	5
Angola	8	4
Kazakhstan	8	4
Libya	8	4
Saudi Arabia	7	3
Venezuela	6	3
Mexico	5	2
Indonesia	5	2
China	4	2
Canada	4	2
USA	4	2
Uzbekistan	4	2
Qatar	4	2
Oman	4	2
Kuwait	3	1
Malaysia	3	1
Top-20	225	113
World	266	133

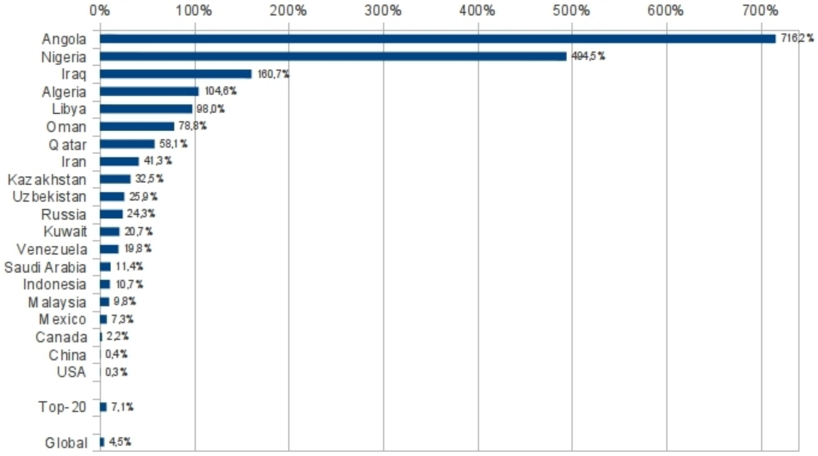

Figure 1.11: Potential electric energy produced by CCGT plants as a percent of total electric supply (data source: NOAA and EIA)

Hypotheses for combined cycle gas-turbine plant (CCGT)

- Nominal power: $800MW$[5]
- Load Factor (LF): 85%
- Efficiency: 56%
- LHV: $38MJ/m^3$

Hypotheses for simple cycle gas-turbine plant (SCGT)

- Nominal power: $250MW$[6]
- Load Factor (LF): 85%
- Efficiency: 35%
- LHV: $38MJ/m^3$

The electric energy obtained over a year in both scenarios is compared to total energy supply of each considered country in figures 1.11 and 1.12.

Because of a weak electric energy supply and a large availability of associated gas, the computed percentage is largely above 100% in some countries, and mostly in Angola, Nigeria and Iraq. Almost in all Top-20 countries the potential electric income is a significant per cent of their energy supply. Obviously, values are higher in the top-efficiency scenario.

Previous observations led to the conclusion that the gas flaring practice is a waste of energy. Moreover, its effect on global and local environment is certainly not negligible (paragraph 1.1.2 addresses the issue of a qualitative and quantitative analysis of this topic).

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[5] This is a typical CCGT plant size.

[6] This is a typical single turbogas size.

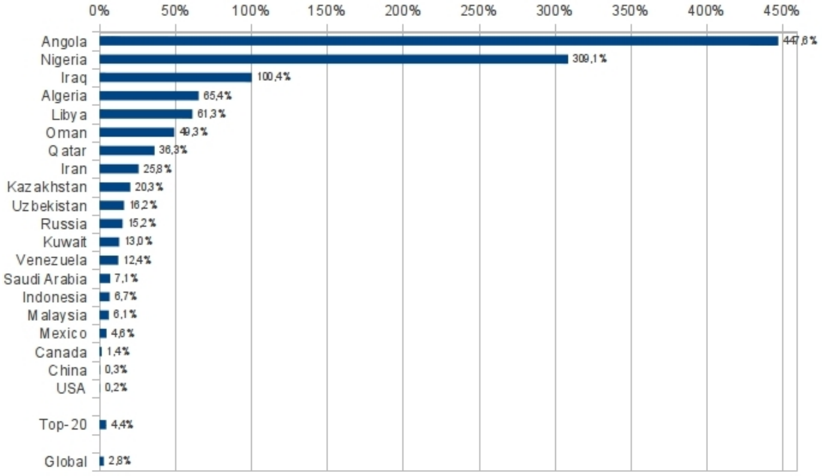

Figure 1.12: Potential electric energy produced by SCGT plants as a percent of total electric supply (data source: NOAA and EIA)

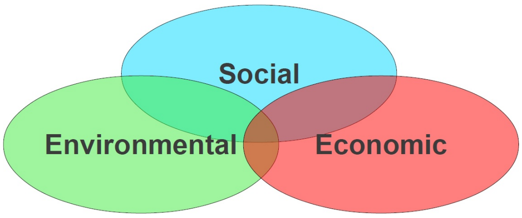

Figure 1.13: Sustainable development

1.1.2 Gas flaring and sustainability

Gas flaring is a bad practice in many other aspect it could be considered. For example, if it is analysed under the sustainability criteria it is evident that gas flaring does not

> meets the needs of the present without compromising the ability of future generations to meet their own needs [4].

As expressed in figure 1.13 sustainability must have three features to be complete: environmental, economic and social ones, that are called the *dimensions* of sustainability.

Environmental impact The environmental effects of gas flaring are also important: not only it uses up fossil resources faster than they regenerate, but it produces also air pollution (mainly NO_x and SO_x), water pollution and soil pollution, it causes the release of greenhouse gases (CH_4, CO_2) and it damages agriculture, too.

In the global context greenhouse gas emissions from gas flaring are negligible: they are about $280 Mton$ compared with a total of over $30000 Mton$. This corresponds to about 1% of the global CO_2 emissions.

Nevertheless, CO_2 emissions due to gas flaring are a significant share of total CO_2 emissions in some countries such as Nigeria and Angola: in table 1.3 are presented CO_2 emissions due to gas flaring of Top-20 countries and the share they represent in total

Table 1.3: CO_2 emissions (calculation based on NOAA's data)

Country	CO_2 emitted for free $[Mt]$	Share of CO_2 emission from flaring
Russia	73.7	4.73%
Nigeria	31.7	40.57%
Iran	23.6	4.46%
Iraq	19.1	17.59%
Algeria	11.3	9.95%
Angola	8.5	35.70%
Kazakhstan	7.9	4.31%
Libya	7.9	14.41%
Saudi Arabia	7.0	1.60%
Venezuela	5.9	3.73%
Mexico	5.2	1.18%
Indonesia	4.8	1.15%
China	4.4	0.06%
Canada	4.3	0.80%
USA	4.3	0.08%
Uzbekistan	3.9	3.39%
Qatar	3.9	6.06%
Oman	3.7	7.55%
Kuwait	3.1	3.73%
Malaysia	3.1	2.06%
Top-20	237	1.30%
World	280	0.92%

country CO_2 emissions[7] [5].

Note that only carbon dioxide (CO_2) emissions from the consumption of energy have been considered as the total emissions, whereas CO_2 emissions from flaring had been computed as follows:

$$CO_{2emissions}[ton] = \frac{LHV_{oil} \cdot MM_{CO_2}}{v_m} \cdot \sum_i \frac{y_i \cdot \nu_i}{LHV_i}$$

where $MM_{CO_2}$is the molar mass of CO_2, ν_i is the stechiometric ratio for the compound i , y_i is the mass fraction for each natural gas compound and v_m is the normal molar volume $(22.414 m^3/kmol)$.

The calculation of CO_2 emissions is rounded down because of considering the difficulty of combustion that results not complete, affected by velocity of wind and many other parameters. Incomplete combustion also produces monoxide carbon, that represents a direct risk for the human health. This is one of the reasons why flare stack are usually positioned vertically. The other reason is that combustion products are more dispersed in vertical stack than in horizontal ones, also reducing noise, smoke, heat and odours at ground near the stack.

Among combustion products with some impact on environment, not only CO_2 and CO can be found. In table 1.4 are shown nitrogen dioxide (NO_2) emissions from flaring and emissions related to an hypothetical combustion of the same gas in a modern turbogas.

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[7] All data refer to year 2009.

Table 1.4: NO_2 emissions (calculation based on NOAA's data)

Country	NO_2 emitted for free [t]	NO_2 emitted in TG [t]
Russia	81374	10172
Nigeria	35040	4380
Iran	26026	3253
Iraq	21069	2634
Algeria	12467	1558
Angola	9413	1177
Kazakhstan	8766	1096
Libya	8762	1095
Saudi Arabia	7762	970
Venezuela	6544	818
Mexico	5769	721
Indonesia	5249	656
China	4881	610
Canada	4778	597
USA	4761	595
Uzbekistan	4310	539
Qatar	4260	532
Oman	4079	510
Kuwait	3448	431
Malaysia	3398	425
Top-20	262155	32769
World	309152	38644

The assumptions for the computation are the following ones:

- 200*ppmvd* adjusted at 15% oxygen dry for combustion in air;
- 25*ppmvd* adjusted at 15% oxygen dry as emissions for a turbogas, that means a reduction of 85%.

Another gas that can be found after a combustion is sulphur oxide (SO_2), with the quantity represented in table 1.5.

In this case the assumptions are:

- SO_2 emissions could be virtually totally avoided by pollutant abatement system, so that a turbogas does not have SO_2 emissions;
- a content of H_2S in the gas equal to 2.5%[8].

Obviously there are many other pollutants among combustion products that have not been considered here on a quantitative level.

Hence, in addition to those already cited, gas flaring has many other important effects on the environment, that had been object of many studies in the past years.

One of the most expectable effects is the notorious acid rains, that means the presence of acid substance and heavy metals in rainwater near the stack. The negative effects have

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[8] `http://www.naturalgas.org/overview/background.asp`

Table 1.5: SO_2 emissions (calculation based on NOAA's data)

Country	SO_2 emitted for free $[t]$
Russia	2385
Nigeria	1027
Iran	763
Iraq	617
Algeria	365
Angola	276
Kazakhstan	257
Libya	257
Saudi Arabia	227
Venezuela	192
Mexico	169
Indonesia	154
China	143
Canada	140
USA	139
Uzbekistan	126
Qatar	125
Oman	120
Kuwait	101
Malaysia	100
Top-20	7684
World	9061

a spatial gradient, such as they are the more important the nearer area is to the stack and they involve water resources, soil, vegetation and other life forms [6].

Emission due to gas flaring include several metals and other toxic substances, that then fall with the rains and deposit in the surface water and on the ground [7]. The presence of heavy metal in the surface water have serious consequences on the wildlife.

Another effects of acid rains and the gas flaring emissions is the change of the soil characteristics, such as pH value, adverse to the ecosystem [8]. These changes in the ground and the high temperatures around the stacks slow down the growth of crops, that means shorter plants, smaller leaves and less nutrients in the crops, as confirmed in studies about Nigeria situation [9].

High temperature, or significant thermal gradient, badly influence also *the socio-economic lives and activities of the inhabitants* [10].

Economic impact In table 1.6 the impact that flared gas could have on the GDP of each country in the case it is sold is shown [11]. It is noticeable that reduction of gas flaring would have important positive effects on region economy especially for development countries (with the peak of Nigeria with over 20% of his GDP literally *burned*).

Obviously this is not a real income because calculation are made without considering extra costs for modify the existing plants (neither investment nor operational and maintenance costs) and supposing a gas value equal to $0.14 USD/m^3$ that was the value of natural gas at December 2010 [12, 13] (that is actually very variable over time).

As a secondary effect each country could increase its income forcing companies to

Table 1.6: Impact of gas flaring reduction on GDP (data source: International Monetary Fund)

Country	Potential income from gas flared as a per cent of GDP
Russia	0.23%
Nigeria	20.85%
Iran	0.20%
Iraq	1.15%
Algeria	0.31%
Angola	0.54%
Kazakhstan	0.29%
Libya	0.62%
Saudi Arabia	0.08%
Venezuela	0.11%
Mexico	0.02%
Indonesia	0.03%
China	0.00%
Canada	0.02%
USA	0.00%
Uzbekistan	0.33%
Qatar	0.20%
Oman	0.34%
Kuwait	0.16%
Malaysia	0.05%
Top-20	0.05%
World	0.03%

reduce gas flaring: gas flaring is obviously free from taxation and royalty payments to the government, whereas reducing gas flaring produce an increase in gas production and sale with consequent growth of royalty [14].

Social impact Gas flaring has also many social implications, some linked to aspects seen previously, some to other aspects.

A first consequence of gas flaring with a clear social impacts is the corrosion of metal due to acid rains, in particular of house roofs in villages in Niger Delta. This is a problem for human because in Niger Delta people use to collect rainwater to drink it, but they collect it using corrugated iron-roofs as ducts, so even if water has been polluted by heavy metal it is used for cooking, for washing and for food [15]. Though being primarily a problem with health effects this also has a socioeconomic impact because of the cost of the replacement and the repair of house roofs affects people income in a tangible way[16].

Obviously this finally has environmental consequences, as it was underlined in the previous paragraph.

People exposed to gas flaring emissions also show an increased probability of getting cancer [17].

Other effects of flaring gas is that stack produce continuously heat, light, noise, smoke that can cause health complications such as insomnia, stress, high blood pressure, heat rashes and many others [16].

The perception people have about the phenomenon in developing countries is very low.

Table 1.7: Official Development Assistance (data source: OECD)

Country	ODA [*Millions* $]	Potential income from gas flared as a per cent of cooperation aids
Russia	–	
Nigeria	687.5	309%
Iran	65.7	2397%
Iraq	2628.7	49%
Algeria	200.3	377%
Angola	131.4	434%
Kazakhstan	172.3	308%
Libya	32.4	1639%
Saudi Arabia	–	
Venezuela	46.9	845%
Mexico	158.7	220%
Indonesia	332.9	95%
China	1156.9	26%
Canada	–	
USA	–	
Uzbekistan	77.4	337%
Qatar	–	
Oman	8.4	2944%
Kuwait	–	
Malaysia	132.9	155%
Top-20	5832.5	272%

Frequently people doesn't have idea of the effects on the environment and on their health, or they are resigned about their situation or simply they don't express their opinion when interviewed because of the fear of retaliation by government or companies [15, 18].

Since developing countries often need the help of the Monetary International Fund in the form of Official Development Assistance (ODA) for economic development and welfare improvement, a quantitative analysis of the social implication of economic impact of flaring gas is the comparison of eventual income from gas flaring reduction with the size of ODA[9] [19] received by a country. It is noticeable in table 1.7 that this ratio is often greater than 1, this means that a reduction of gas flaring and the consequent income by selling recovered gas would be more important than international aid these countries annually receive.

1.2 Opportunity for low developed countries

1.2.1 The issue of access to energy

The Advisory Group on Energy and Climate Change (AGECC) individuate three incremental levels of access to energy services, each of them characterized by the benefits provided [20]:

- **Basic human needs**: electricity for lighting, health, education, communication and community services; Modern fuels and technologies for cooking and heating.

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[9] ODA total, net disbursement (constant prices, 2009 millions $).

Table 1.8: Energy and development indicators (data source: World Bank 2008)

	Income threshold per capita [$]*	*HDI*	Population [Millions]	GNI per capita [$]	TPES per capita [*toe*]	EI
Low income countries	< 1005	0.31	976	523	0.42	0.31
Middle income countries	≤ 12275	0.56	4652	3251	1.24	0.23
High income countries	> 12275	0.8	1069	39669	5.32	0.15
World			6761	8654	1.80	0.19

* Year 2010, using World Bank Atlas method.

- **Productive uses**: Electricity, modern fuels and other energy services to improve productivity (water pumping for irrigation, fuels for transports, . . .).
- **Modern society needs**: Modern energy services for many more domestic appliances, increased requirements for cooling and heating, private transportation.

On the basis of these levels AGECC in [20] defines universal energy access as

> access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses

i.e. levels 1 and 2. The term “affordable” is adopted meaning that

> the cost to end users is compatible with their income levels and no higher than the cost of traditional fuels.

In any case it is clear that nowadays energy is at the heart of most critical economic, environmental and developmental issues. Clean, efficient and affordable energy services are indispensable to ensure decorous life conditions. In poor countries current energy systems are inadequate to meet their needs: in fact about 25% of the world population has no access to electricity and up to a billion of people have access only to unreliable energy networks.

For this reason the lack of access to energy, and in particular of access to electricity, can be seen as a marker of the lack of development [21]: according to the General Assembly of the United Nations and to the United Nation Millennium Goals [22], access to energy is an essential requirement to defeat poverty. As a matter of facts, a lot of essential human activities are linked to energy disposal: heat and electricity are fundamental to ensure medical assistance, food cooking, water pumping and purification, but also to improve school attendance and to give access to information.

According to a World Bank study [23] underperfoming energy systems cause a loss of potential annual growth up to $1-2$ per cent of GDP as a result of power outages, over-investment in emergency generators, ...

In table 1.8 [21] data of the year 2008 are introduced: it is clear that there is a strong connection among Human Development Index (HDI), Total Primary Energy Supply (TPES) per capita and the energy intensity (EI), which is the rate between TPES and

Table 1.9: Energy and development indicators for Top-20 countries (data source: IEA; OECD; World Bank; 2009)

Country	*HDI*	Population [Millions]	GNI per capita (Atlas method)* [$]	TPES per capita [*toe*]	EI
Russia	0.719	142.9	9340	4.56	0.42
Nigeria	0.423	162.4	1190	0.70	0.60
Iran	0.702	75.8	4530	2.97	0.37
Iraq	0.583**	32.1	2210	1.11	1.02
Algeria	0.677	36.3	4420	1.14	0.18
Angola	0.403	19.6	3750	0.64	0.22
Kazakhstan	0.714	16.6	6920	4.14	0.49
Libya	0.755	6.4	12020	3.18	0.29
Saudi Arabia	0.752	27.1	17700 (approx.)	6.22	0.42
Venezuela	0.696	29.4	10090	2.36	0.35
Mexico	0.750	112.3	8960	1.63	0.16
Indonesia	0.600	237.6	2050	0.88	0.22
China	0.663	1339.7	3650	1.7	0.18
Canada	0.888	34.5	41980	7.53	0.25
USA	0.902	312.6	46360	7.03	0.19
Uzbekistan	0.617	27.8	1100	1.76	0.73
Qatar	0.803	1.7	Not available	16.91	0.65
Oman	0.846***	2.8	17890 (approx.)	5.29	0.31
Kuwait	0.771	2.8	43930 (approx.)	10.80	0.42
Malaysia	0.744	28.7	7350	2.43	0.22

* World Bank, 2010

** Year 1998, Human Development Report 2000

*** Year 2007, Human Development Report 2009

GNI (Gross National Income): TPES is approximately proportional to HDI; energy intensity[10], at the contrary, is in inverse proportion to HDI. The so-called developed countries, characterized by high income economies, show a high mean value of HDI and TPES, but a low value of energy intensity, while the exact opposite is valid for developing countries characterized by low income economies.

In order to collocate Top-20 countries in their context, a summarize of these data is presented in table 1.9 [25].

For example, currently Africa has 14% of the world population and consumes only 3% of the world produced electricity, instead about 9% of the world population lives in Europe, where more than 19% of the world electricity is consumed [26], and in general the number of people without access to electricity is very large in developing regions (table 1.10).

Often countries with low income economies make use of inefficient technologies, too, so that low conversion efficiencies and the lack of exhaust gas treatment systems causes strong quantities of dangerous emissions that affect humans and environment. This is true in power plants contexts but also in domestic contexts, and World Health Organizations states that indoor air pollution from solid fuels is the *4th* cause of illness and death in

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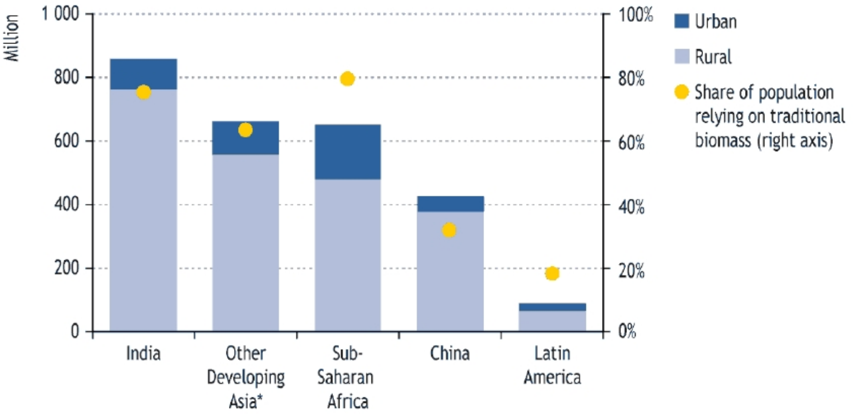
[10] Energy Use per unit of GDP [24].

Table 1.10: Number of people (million) without access to electricity (data source: OECD; IEA; 2009)

Region	**Rural**	**Urban**	**Total**
Africa	466	121	587
Sub-Saharan Africa	465	120	585
Developing Asia	716	82	799
China	8	0	8
India	380	23	404
Other Asia	328	59	387
Latin America	27	4	31
Developing countries*	1229	210	1438
World**	1232	210	1441

*Includes Middle East countries.

**Includes OECD and transition economies.



*Includes developing Asian countries except India and China.

Figure 1.14: Number and share of population relying on the traditional use of biomass as their primary cooking fuel by region (data source: OECD; IEA; 2009)

developing countries, mostly because of inadequately ventilated buildings [27]: biomass is largely used in poor countries because of the absence or the excessive price of other fuels. In particular, women and girls in the developing world are disproportionately affected in this regard.

Figure 1.14 shows the amount of population relying on traditional use of biomass as their primary cooking fuel by region.

Moreover, this practice causes the serious additional environment impact of deforestation, and, consequently, of desertification [28].

The use of natural gas, LPG or other fuels and the improvement in electricity availability could mitigate these problems, and give an impulse to education and life quality, specially for what concerns women and children conditions.

Clearly, energy access is a complex issue, characterized by cultural, political and technical aspects strongly dependent from specific situations, so that the proposal of a single solution is not acceptable, but in any case an appropriate mix of efficient technologies and

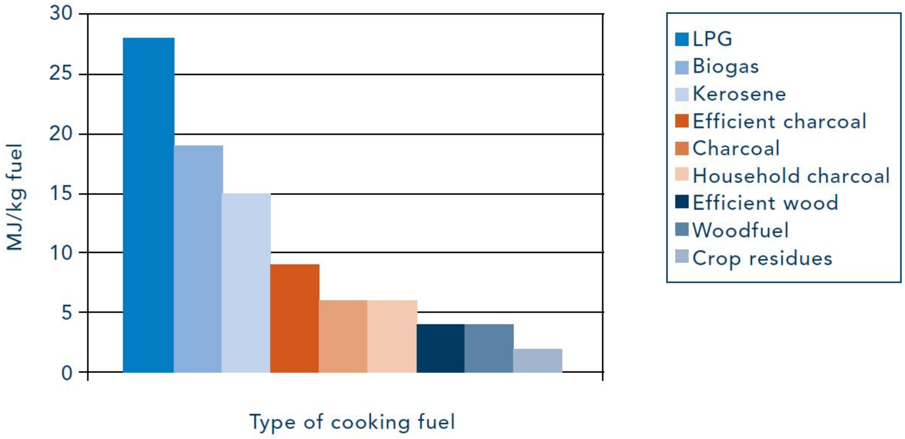


Figure 1.15: Energy efficiency of selected cooking fuels (data source: FAO, 2000)

adequate policies is needed to improve energy access and fighting poverty.

1.2.2 Gas flaring reduction: an opportunity for energy access

The previous section showed the energy waste due to gas flaring.

It is easy to notice that a good part of the Top-20 countries are developing countries, that means countries where energy access is not always assured with adequate reliability.

In these countries gas flaring reduction could make available large quantities of natural gas or other products like LPG and synthetic fuels deriving from associated gas processing. These products could feed thermal power plants to obtain electricity or could be employed in other activities and especially as a substitute of wood used for cooking.

In particular, LPG is widely utilized in cooking applications, providing much more efficient use of energy than biomass, as figure 1.15 shows.

The Nigerian case is the most representative example of this opportunity: about 148 million inhabitants live under the poverty threshold and about 90% of population live with less than 2 dollars per day [29]. About 95 million people depends on wood for their daily cooking. Wood energy constitutes nearly 40% of primary energy consumption, indispensable to satisfy cooking and heating needs. In Nigeria wood energy satisfies about 90% of total household energy use [30], and about 60% of population has no access to electricity.

Energy from associated gas could be used for pumping clean water from wells close to villages, to grant efficient cooking reducing indoor air pollution, cutting household energy costs and time lost in gathering fuel wood. This time could be used by children and adults (and in particular women) for education or to develop small businesses [31].

The distribution of gas or liquid fuels in villages could also constitute an opportunity of business in itself, specially if committed to local cooperatives.

Large-scale LPG programs in Brazil and Senegal demonstrate that rural distribution challenges can be overcome, while at the same time creating local jobs and livelihoods [32, 33].

Furthermore, the substitution of wood fuels or other fuels like coal or fuel oil by natural gas implies a reduction of the carbon intensity, that is the amount of carbon emitted per unit of energy produced, both because of the intrinsic chemical characteristics of the gas and because of the fact that reducing wood demand means contrast deforestation and desertification.

1.3 World Bank's initiative: a voluntary partnership

Data given in section 1.1 lead to the conclusion that gas flaring or, still worse, venting, represents not only an economic loss, but causes also environmental damages both at a global and local level, health problems to people that lives near stacks, and so on. Section 1.2, moreover, showed how the reduction of gas flaring can allow also to improve energy access conditions in developing countries. Nevertheless, it is worldwide recognised that solving the problem of gas flaring is very complex, also because it involves various stakeholders, each one with different interests.

This is why many international organizations deal with this objective.

The most important one is the World Bank with its Global Gas Flaring Reduction initiative (GGFR): Global Gas Flaring Reduction is a public-private partnership that was launched at the World Summit on Sustainable Development in Johannesburg in 2002. The final goal of GGFR is the global reduction of flaring and venting practice, that means to somehow use associated natural gas, in order to preserve the environment and to not waste energy resources.

1.3.1 Main stakeholders

In the broader conception, the term *stakeholder* refers to any person or organization who can be positively or negatively impacted by or cause an impact on a project.

Before describing in detail the World Bank's initiative it is necessary to understand who are main stakeholders of a gas flaring reduction project, that can be grouped in the following categories: oil companies, other costumers and infrastructure owners, governments and international organizations involved in reducing gas flaring. Therefore, in next paragraphs these categories are introduced, also with tools available to each of them to obtain maximum benefit from gas recovery [34, 35].

Gas producers

Often gas producers are not interested in reducing gas flaring because of the poor or negative economic return that concerns to this kind of projects in most situations. However, in most of world's countries continuous gas flaring is forbidden and subjected to penalties, so that also reducing gas flaring with a project characterized by a poor economic return can mean saving money for gas producers.

Moreover, if the project meets the eligibility criteria, a carbon credit mechanism, either within the Kyoto Protocol framework, like Clean Development Mechanism or Joint Implementation[11], or outside the Protocol can be employed to obtain a reduction of project cost. Gas producers should also examine integrated economics integrating the revenues from both the oil and gas production from the field, so that the viability of a project may be enhanced.

Eventually, they should consider to expand project boundaries to other producers or customers encouraging maximum local gas utilization to supply thermal or electrical needs.

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[11] See paragraph 1.3.2 for further information about carbon credit mechanisms.

Local governments

Local governments have a strong impact on diffusion of gas flaring or venting practices: they should define clear rules about associated gas utilization. In many cases standards about flaring are not clearly specified and because of this fact gas producers are not encouraged to engage in gas recovering projects. This includes large oil-producing nations such as Algeria, Angola, Indonesia, which do not have specific guidelines.

In some cases, countries that have set flare and vent reduction targets have not yet implemented an efficient gas sector strategy and regulatory framework required to achieve real reductions in flare and vent volumes. For example, Nigeria is currently developing a relevant strategy and framework. Other countries, at the contrary, regulate gas flaring and venting through primary and secondary legislation. To give an example, this is the case of Norway, United Kingdom, Canada and other countries. A complete report about gas flaring national legislation is given in [36].

Governments should promote associated gas' prices so that its real value is recognized without penalizing costumers by imposing excessive prices: gas price should be fixed considering prices of alternative fuels that can be replaced making use of the recovered gas. The price should also take into account environmental benefits due to the substitution of other fuels with natural gas.

The definition of a national strategy about gas market could detect its main constraints: local governments have an essential role in mitigate or remove market constraints on associated gas utilization creating or stimulating gas markets' development or providing incentives for both gas producers and costumers. Product sharing contracts (PSCs) can encourage investments in gas gathering and other infrastructures, recognizing extra costs associated to gas recovering; in the same way, the institution of a tax on gas flaring and incentives on emission reduction or special tax credits for investments can encourage reduction of the practice, too.

Furthermore, governments should coordinate different stakeholders to improve opportunities for gas utilization: frequently gas producers, costumers and other stakeholders do not operate together and because of this fact in practice they do not take advantage of some opportunities.

Lastly, governments can promote development of markets of products derived from associated gas conversion such as electricity or synthetic fuels.

Costumers and infrastructure owners

Commercial and industrial costumers could trade long-term contracts about associated gas to meet producers needs. In particular gas purchasers should accept contracts involving low swing factors so that they do not invalidate benefits deriving from oil production to whom gas production is associated.

Costumers should also purchase agreements for relatively small volumes of gas that might be difficult to market. Field depletion based contracts will generally be attractive to gas producers. Gas buyers have to notice that gas value has to be compared with that of alternative fuels, and to consider the opportunity of substitution of these fuels (for example coal or fuel oil) with associated gas. Therefore an appropriate gas price should also reflect environmental benefits deriving from gas utilization.

A further incentive for producers is achieved adopting take or pay contracts. In fact this type of contract can significantly reduce the market risk when the recovery of associated gas is perceived to be financially risky.

Similarly, providing payment guarantees for associated gas can stimulate capital investment in gas recovery facilities with medium or long-term payback; the provision of payment guarantees by buyers can also reduce the market risks such as to induce the necessary investment when a gas recovery project is financially marginal.

Gas infrastructure owners should evaluate new investments to extend gas transfer capacity and maximize utilization of existing infrastructures, to prioritize the purchase of associated gas to assure observation of commitments under existing gas contracts, to transfer third-party gas collecting reasonable tariffs established taking into account the final selling price.

In some circumstances, when investments are particularly large, infrastructure owners should evaluate the opportunity of participating in capital investment together third-part owners.

International organizations

The World Bank is the most famous of these organizations but there are many others like Methane to Market international initiative, Asian Development Bank, ...

These organizations can have a strong role in encouraging local governments to undertake actions with the aim of reducing or eliminating this practice, especially in countries where governments don't have sufficient technical knowledge to define clearly a legislation about flaring or are not interested in solving this problem. They can provide governments with common guidance to assist country objectives about flaring and venting reduction and to develop potential gas markets to promote associated gas utilization.

They can also encourage cooperation between industry and governments by defining mutually agreeable and consistent objectives and targets, suggesting the implementation of best available technologies and practices (including gas refining and processing into fuels and petrochemical products) to bring gas flaring and gas losses down.

Some international organization allocate funds to support flaring reduction projects.

Civil society

In addition to these categories identified by World Bank, also populations living in regions where gas wells are situated should be involved. The involvement of local associations or groups of citizens in the decision process could avoid possible protests and disputes that are generally typical of this kind of projects, especially when the plant is near a city or in a environmentally sensible site.

1.3.2 Global Gas Flaring Reduction initiative (GGFR)

GGFR initiative is supported by the following main partners that are also stakeholders [37][12]:

- **gas producers**: BP, Chevron, ConocoPhillips, Eni, Exxon Mobil, Marathon Oil, Maersk Oil & Gas, NNPC, Pemex, PetroEcuador, Pertamina, Shell, Sonatrach, Sonangol, SOCAR, SNH, StatoilHydro, TOTAL, Qatar Petroleum;
- **local governments**: Algeria, Angola, Azerbaijan, Cameroon, Canada, Chad, Ecuador, Equatorial Guinea, European Union, France, Gabon, Indonesia, Iraq, Kazakhstan,

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[12] Civil society cannot be considered a direct partner but obviously has the role of stakeholder, as was said previously.

Khanty-Mansisysk (Russian Federation), Mexico, Nigeria, Norway, United Arab Emirates, United States, Uzbekistan;

- **international organizations**: European Union, IFC, Masdar Initiative, OPEC Secretariat.

To achieve its goal GGFR makes companies and governments sit down at the negotiating table, carry out a plan and make the project effective. The role of an international organization such as World Bank is essential to overcome the constraints (market, company and technical ones, as explained in section 1.1).

In particular GGFR utilizes Kyoto mechanisms, systems that allow countries and companies that agreed with the Kyoto Protocol to reach a better limitation or to reduce greenhouse gas emissions. This instruments are Clean Development Mechanism (CDM), Joint Implementation (JI) and Emission Trading (ET).

Clean Development Mechanism is the only mechanism that requires cooperation between developed countries and developing countries, exactly CDM can be used by developed country that want implement a project of GHG reduction in developing ones. In so doing it is expected to help hosting countries to achieve sustainable development, obviously in addition to the global GHG reduction.

Accessibility of CDM is due to some criteria; the most important are:

- additionality of GHG reduction: projects that are eligible for CDM are those that avoid the emission of GHG that would be emitted without the implementation of the projects instead[13];
- promotes sustainable development: CDM projects must satisfy national sustainable development goals and priorities of the host country;
- measurable results: projects must include a monitoring phase that can measure GHG reduction.

To be considered eligible for CDM a project need also a valuation and validation by third bodies and emission reduction must be certified.

Joint Implementation mechanism concerns projects that reduce GHG emissions undertaken by developed countries and implemented in other developed countries.

JI criteria of accessibility focus more on countries' attributes (as for examples the joining to the Kyoto Protocol or the existence of a structure about GHG measurement) than on projects' features. If a country satisfies these requirements it can undertaken the project, otherwise international and independent organizations are involved, an evaluation procedure, similar to CDM one, is needed and additionality criterion is added.

An **International Emission Trading** is a system that consist in allowing countries to trade in order to satisfy GHG reduction obligation imposed by Kyoto Protocol. A government or a company can implement a GHG reduction project and than to sell the exceeding rights to emit to another entity. Many trading programs have been created outside the system planned with the Kyoto Protocol, both on a national scale and on a regional scale and within international oil companies.

The GGFR is in a unique position to be a platform for exchanging ideas and experiences on CDM/JI flaring reduction projects and other activities that would promote such investments: as a matter of facts lack of experience and examples that could guide the project cycles is an important obstacle for gas flaring reduction projects requiring

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[13] The UNIDO (United Nations Industrial Development Organization) guidelines seem to exclude any project hosted in a country in which reductions are required by law.

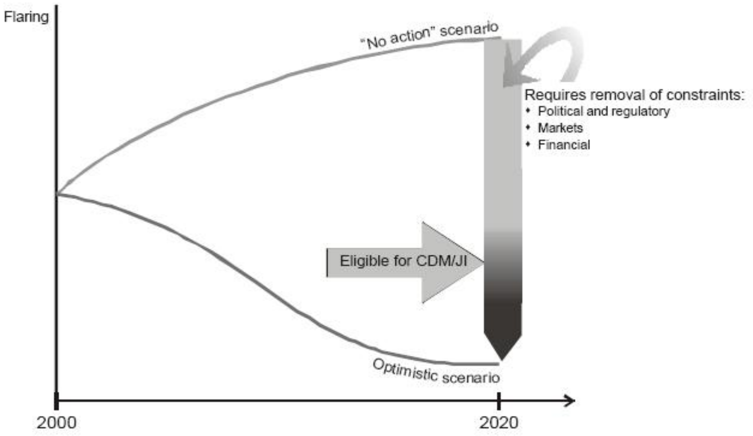

Figure 1.16: Scenario for global flaring of associated gas

CDM/JI eligibility. In figure 1.16 is presented the estimated reduction of gas flaring with the eligibility for CDM/JI of these projects.

The surplus value of GGFR compared with individual initiatives is a better organization during the project cycle and, in the future, a greater experience in the removal of the obstacles in the realization of the projects.

As time goes by and with more projects undertaken, experience in flaring reduction projects will be gained and potential costs due to the GGFR structure will decrease.

Are flaring reduction investments eligible for carbon credits?

An important matter is the eligibility of flaring reduction investments for carbon credits. Mechanisms do not exclude particular areas of action, so these kind of projects cannot be excluded a priori. The eligibility of a project is not prevented neither in presence of a possible affordability of the project without acceding to Kyoto mechanisms. In these case it is important the presence of another constraint that keep eligibility of the project.

In [37] there is a deep analysis of three projects concerning gas flaring reduction that shows the full applicability of Kyoto mechanisms to real projects.

The three projects are the expansion of a power station in the Tomsk Region (Russia), the construction of a pipeline in West Africa (both of them are known from several years, respect all the eligibility criteria of CDM/JI mechanism and are commercially viable, but they are not be implemented yet[14]) and a gas re-injection project in Asia (in 2004 was at a planning stage).

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[14] In 2004.

Chapter 2

Facilities and main technologies suitable for reducing gas flaring

2.1 Common facilities

In chapter 1 the fact that gas associated to oil extraction is often flared was underlined.

Figure 2.1 shows a typical flow diagram of an oil plant where associated gas is burned in a stack. In the diagram the gas treatment unit is represented with a sketched boundary because it is not always used: sometimes raw gas is directly burned nevertheless the presence of sulphurous compounds, mercury and other several pollutants that cause very serious local pollution (as shown in paragraph 1.1.2).

Starting from this typical situation, it is necessary to choose a technological alternative to reach the sustainability and making possible to switch off gas flares at production sites.

Most significant ways to convert or make use of associated gas are:

- On-site re-injection
- Pipeline transportation to industrial or domestic costumers
- Liquefied Petroleum Gas and Liquefied Natural Gas processes
- Power generation (gas to power)
- Gas To Liquid processes or methanol production.

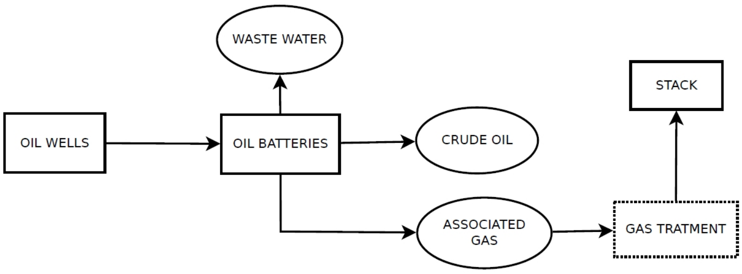

Figure 2.1: Flow diagram of oil wells with flaring stack

Clearly, not all of these technologies can be used in all contexts. Therefore, in a first step it is necessary to verify the feasibility of each one from a purely technical point of view, and in a second step it is necessary to choose the one that allows to obtain the best overall performance, i.e. the one that obtains the best level of sustainability in the hypothesis that is the goal to be reached[1].

Flow diagram in figure 2.2 shows that, except on-site re-injection, other technologies and processes presented need the development of some common facilities to be added to a previous standard plant configuration (i.e. a configuration in which gas is burned). For this reason, before analyzing technologies, in the next paragraphs these facilities are described[2]:

- Gathering pipeline
- Gas oil separation plant
- Gas treatment facilities
- Conditioning unit.

2.1.1 Gathering pipeline

A network of gathering pipelines is necessary to bring crude oil and associated gas from wells to a treatment plant or a processing facility (figure 2.3).

Usually these pipelines are short and with small diameters, but they converge in a long pipe with larger diameter if distance between wells and plants are wide: the size can vary from 2 up to 60 inches ($51mm$ to $1500mm$) in diameter. Gathering pipelines are laid onshore as well as offshore to gather gas from offshore fields. Frequently onshore pipelines are buried at a depth of about 1 to $1.8m$.

If wells pressure is not sufficient, the raw flow of oil and associated gas has to be pumped. In this case oil must be separated from gas to prevent pumps damaging. As an alternative, it is possible to adopt a multiphase pumping configuration: multiphase pumps can boost a raw flow consisting of oil, water, gas and small amounts of solids through a single flow line to the treatment facility [42].

Carbon steel is the most common material, but in case of particularly aggressive flows Corrosion Resistant Alloys (Inox, Duplex, SuperDuplex) or polymeric pipes are used.

2.1.2 Gas oil separation plant (GOSP)

In this facilities (figure 2.4) separation of gas and waste water from oil occurs. To reach an optimal separation a multi-stage process is required. Often a three-stage configuration is adopted. Production separators come in many forms and designs, but the most common variant is the gravity separator.

The flow coming from wells is fed into an horizontal vessel where water settle at the bottom, gas bubbles out and oil is taken out in the middle (figure 2.5). Between one stage and the subsequent pressure is reduced with a choke valve to achieve maximum liquid recovery and stabilized oil and gas. At the end of the process water content is typically

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[1] From now on, this assumption will always be valid even where not explicitly specified.

[2] General reference bibliography for this section: H. Devold, *Oil and gas production handbook* [38]; Arthur J. Kidnay, William R. Parrish, *Fundamentals of natural gas processing* [39]; Peters M. S., Timmerhaus K. D., *Plant design and economics for chemical engineers* [40]; Global methane initiative guidelines [41].

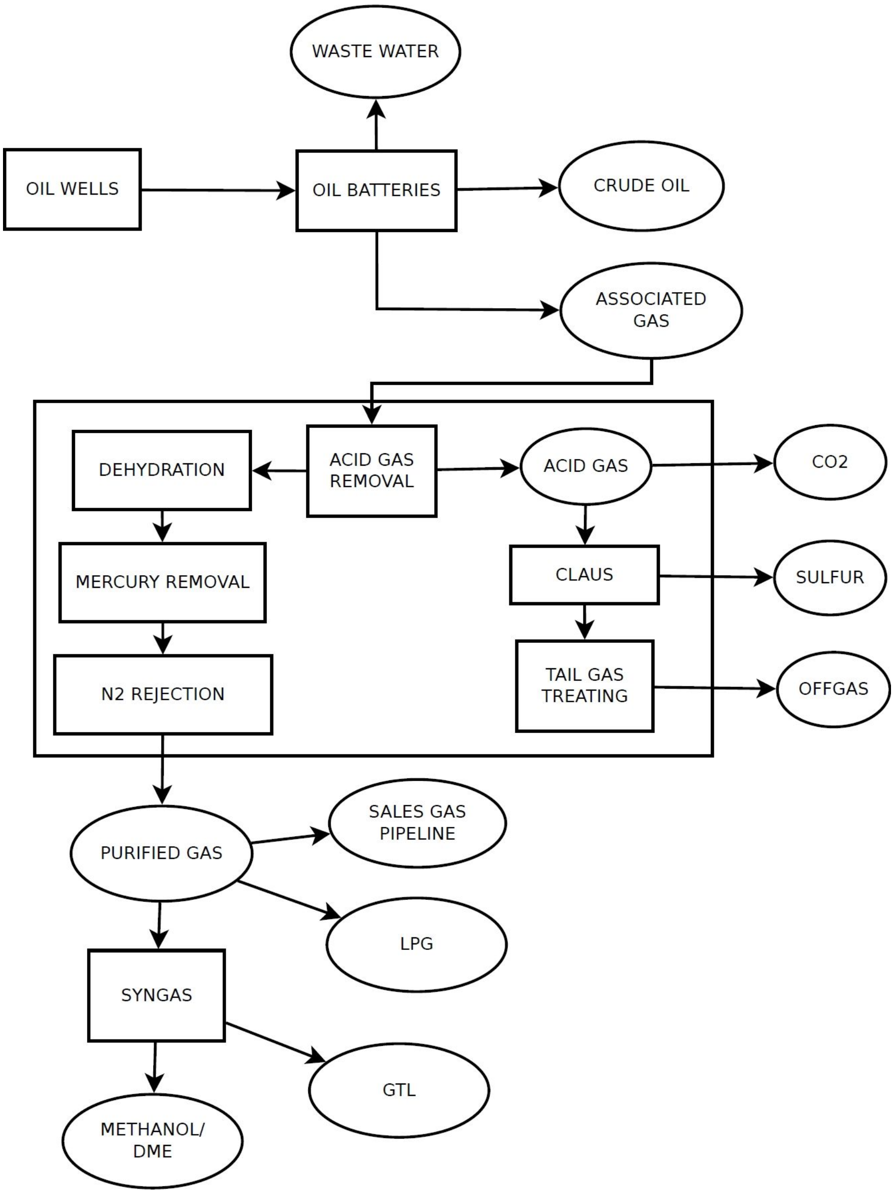


Figure 2.2: Flow diagram of oil wells with associated gas recover process

Figure 2.3: Gathering pipelines (source: Gazprom)

Figure 2.4: Gas oil separation plant (source: Saudi Aramco)

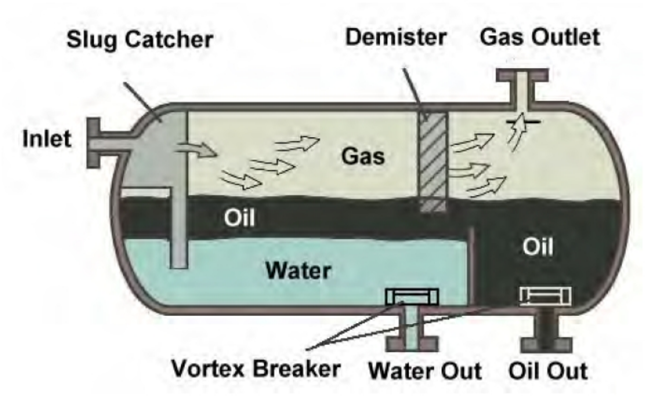
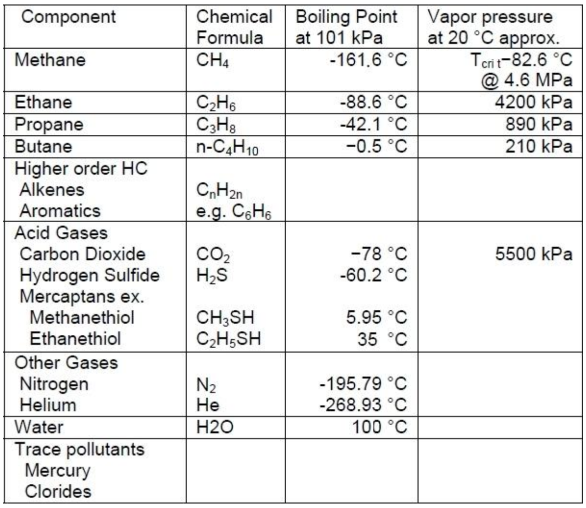


Figure 2.5: Gravity separator

Table 2.1: Main raw gas components (data source: Air Liquide Gas Encyclopedia)



Component	Chemical Formula	Boiling Point at 101 kPa	Vapor pressure at 20 °C approx.
Methane	CH_4	-161.6 °C	T_{crit}–82.6 °C @ 4.6 MPa
Ethane	C_2H_6	-88.6 °C	4200 kPa
Propane	C_3H_8	-42.1 °C	890 kPa
Butane	n-C_4H_{10}	−0.5 °C	210 kPa
Higher order HC			
Alkenes	C_nH_{2n}		
Aromatics	e.g. C_6H_6		
Acid Gases			
Carbon Dioxide	CO_2	−78 °C	5500 kPa
Hydrogen Sulfide	H_2S	-60.2 °C	
Mercaptans ex.			
Methanethiol	CH_3SH	5.95 °C	
Ethanethiol	C_2H_5SH	35 °C	
Other Gases			
Nitrogen	N_2	-195.79 °C	
Helium	He	-268.93 °C	
Water	H2O	100 °C	
Trace pollutants			
Mercury			
Clorides			

reduced to less than 2%. The slug catcher at the inlet reduces negative effects of large gas bubbles or liquid plugs.

To increase separation efficacy the third stage can be replaced by a flash drum, too.

The retention period in each stage is typically 5 minutes.

2.1.3 Gas treatment facility

Raw associated gas consists of methane and many other components (table 2.1). Sales pipeline gas specification is less than 2% CO_2, while normally in sour raw gas it reaches $20 - 40\%$, so it is necessary a gas treatment facility (figure 2.6). Principal components of this facility are introduced hereafter.

Figure 2.6: Gas treatment plant (source: Gazprom)

Acid gas removal

Acid gases represent a problem for equipment and pipelines because they form acids reacting with water. Moreover, hydrogen sulphide and other compounds are toxic and cause environmental pollution.

Several principles are available for the removal process. The most important are the following:

Absorption Acid gases are dissolved in a physical or chemical solvent inside an absorption column and released in a second stage by a process of regeneration. Amine absorption is one of the most common process adopted (most common fluids are monoethanolamine or methyldiethanolamine). A typical amine gas treating process (figure 2.7) consists of an absorber unit, a regenerator unit and accessory equipment. In the absorber, operating at high pressure and low temperature, a lean amine solution absorbs H_2S and CO_2 from the up-flowing sour gas to produce a sweetened gas stream as a product. The rich amine solution contains the absorbed acid gases and is routed into the regenerator (a stripper with a reboiler) so that a concentrated flow of CO_2 and H_2S is released at the top of this column thanks to high temperature and low pressure: typical operating conditions in the absorption unit are $35 - 50°C$ and $5 - 200 atm$, while in the regenerator are $115 - 125°C$ and $1.4 - 1.7 atm$.

Adsorption process is an alternative to absorption: in this case acid gas are captured by a bed of apposite solid materials. After some time the material is regenerated to release gas with a pressure-swing or a temperature-swing based process.

Cryogenic removal constitutes a further way to separate acid gas when there is a high content of carbon dioxide in the raw gas: in this case a gas turbine is driven by the expanding gas which then cools to below the dew point for removing the gas.

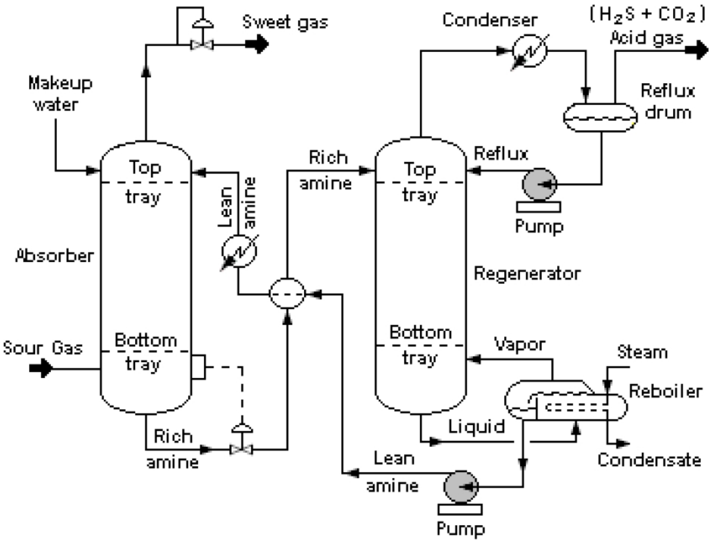


Figure 2.7: Amine gas treating unit

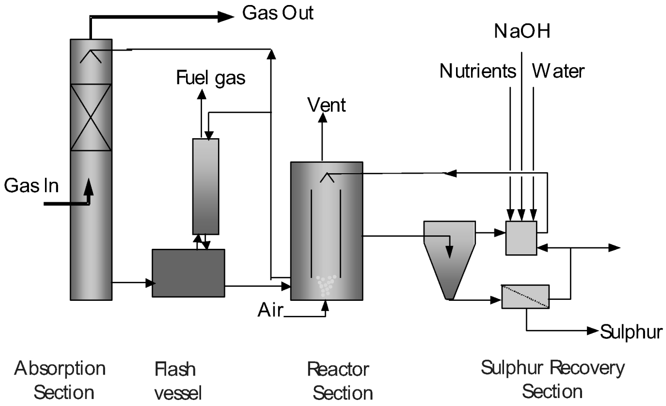


Figure 2.8: Biological desulphurization

Membrane removal is based on materials that allow acid gas to diffuse through themselves but are impermeable to hydrocarbons. Membranes don't need chemicals and are particularly suitable in case of little quantities of raw gas thanks to their modular nature and little economy of scale.

The H_2S-rich flow is fed to a multi-stage Claus process where in a thermal section H_2S is oxidized to SO_2. A catalytic section allows H_2S to react with SO_2 with alumina or titanium dioxide (TiO_2) to produce water and elemental sulphur. The process can recover $95-97\%$ of the sulphur in the feed gases. An additional tail gas treatment (SCOT process is the most common) can increase sulphur recovery up to 99.9%.

An alternative to chemical-based desulphurization is biological desulphurization (figure 2.8): in this case H_2S is removed from the gas stream by mild alkaline caustic solution. The solution is than regenerated in a bioreactor via naturally occurring sulphur-oxidizing bacteria.

Biological desulphurization reaches the goal of elemental sulphur recovery with 100%

selectivity over CO_2 and presents a wide operative range ($1 - 100 bar$; $15 - 48°C$) [43].

Dehydration

Commonly a glycol-based scrubber or a Pressure Swing Adsorption column (PSA) performs this operation.

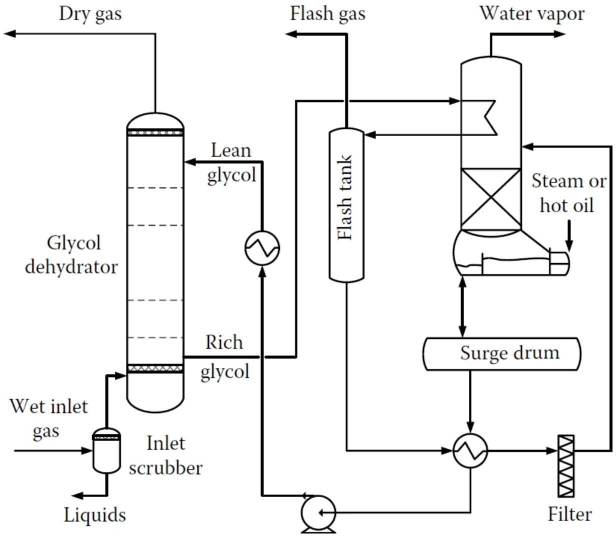


Figure 2.9: Dehydration unit

The most common scrubber makes use of Triethylene Glycol (TEG, figure 2.9).

The wet gas passes through an inlet scrubber to remove solids and free liquids, and then enters the bottom of the glycol contactor. Here it is forced to bubble from the bottom up to the top flowing through the absorber. Lean glycol solution is injected at the top of the column and flows from level to level until it arrives at the bottom from where a rich glycol solution comes out. Rich glycol at first is pumped in a flash tank and than in a reboiler at a temperature of about $130 - 180°C$ that causes water evaporation.

PSA process makes use of an adsorption bed operated at high pressure. Regeneration takes place thanks to a strong pressure reduction (figure 2.10).

In case of small gas streams, dehydration by polymeric membranes is an interesting alternative solution, that can be easily coupled to a membrane acid gas removal unit. Most common membranes are based on hollow fibres allowing selective water permeation.

Mercury removal

Mercury corrodes brazed-aluminum heat exchangers as it amalgamates with the aluminum to weaken the material and is characterized by a high level of toxicity.

In some cases raw gases contain sufficiently high mercury concentrations to cause both safety and health concerns.

Mercury removal is generally based on molecular sieves, i.e. porous substances such as carbons activated with silver that operates as a chemisorbent: silver forms an amalgam with mercury that can be decomposed at higher temperatures ($200 - 300°C$).

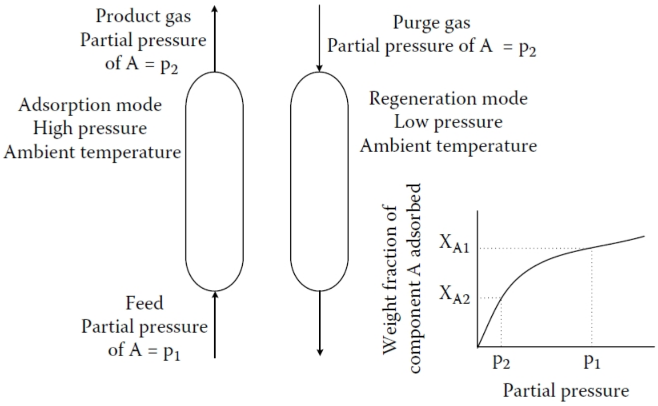


Figure 2.10: PSA unit functioning

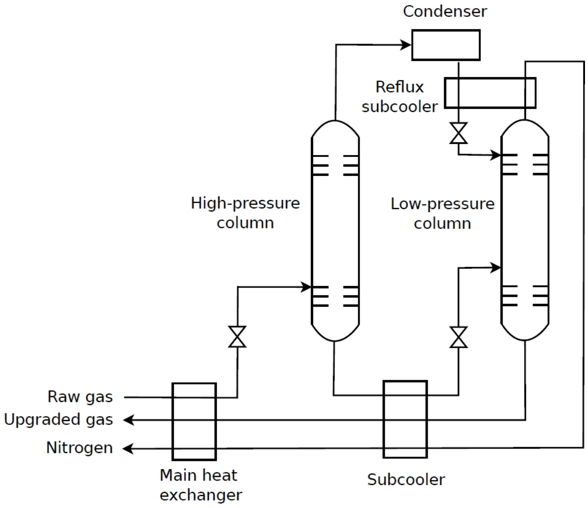


Figure 2.11: Nitrogen rejection unit

Nitrogen rejection

The most common method of removing nitrogen from natural gas is cryogenic distillation.

For feed concentrations below 20% N_2, a single-column design can be used. For higher concentrations, a dual-column is better.

Figure 2.11 shows a two-column plant design.

Firstly gas is cooled by heat exchange and pressure reduction and fed to a distillation column operating at about $10 - 15bar$. The bottoms product from this high-pressure column is reduced in pressure to cool the stream to $120K$. This stream, combined with the bottoms product from the second low-pressure column, is fed to a heat exchanger in the top of the high-pressure column to provide a reflux. The overhead from the high-pressure column flows through a battery of heat exchangers, is expanded to approximately $1 - 2bar$, and enters the low-pressure column at $90K$. The overhead from this column is composed for more than 95% of N_2.

An alternative system to remove nitrogen is a standard Pressure Swing Adsorption unit.

Figure 2.12: Conditioning unit (source: OIEC group)

2.1.4 Conditioning (LPG recovery)

Natural Gas in its marketable form has been processed for a specific composition. Content is typically 90% methane, with 10% other light alkanes. At the contrary, very often associated gas contains significant fractions of ethane, propane and butane in addition to methane (20% on the average, but composition has significant variations from well to well).

A conditioning unit separates methane from these heavier hydrocarbons (figure 2.12). The most common method to obtain this separation is cryogenic separation, in particular based on a turbo expander: the expansion causes gas cooling so that ethane and heavier components condense and are separated from methane.

If GOR is moderate[3] condensates flow is negligible among oil flow: in this case it is possible to mix condensates with oil and avoid marketing a third product.

Contrariwise, if GOR is larger it is necessary to recover commercial LPG. To reach market specifications[4] one or more distillation columns extract ethane, propane, butane and heavier components.

Anyway, it is common to make a separation of the gas, obtaining C_{5+} (then mixed in the oil) and methane, ethane, C_3 and C_4 that are used as fuel for the plant needs. Eventual exceeding is flared.

2.2 Technological alternatives

Once established the need to use in almost every case some common facilities and have explained them in the previous section, analysing proper technologies and processes eligible

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[3] This is a typical situation in case of gas associated to oil production.

[4] Most common commercial LPG is a mix of propane and buthane with ethane up to 4% molar and C_{5+} up to 1% in volume.

Figure 2.13: Gas re-injection head-well (source: Carbon Mitigation Initiative Library)

to reduce or eliminate gas flaring is a logical continuation of the discussion. Therefore, these technologies and processes are described in this section[5].

2.2.1 On-site re-injection

Once a well flow has been treated in oil batteries, separated raw gas can be recovered and re-injected in oilfield through re-injection wells (figure 2.13).

This operation decreases the rate of pressure decline in the reservoir and oil production results enhanced, also because gas molecules dissolve in the oil lowering its viscosity (without re-injection operations recovery of hydrocarbons in a well is generally limited to 50% in case of heavy crudes and $75 - 80\%$ in case of light crudes).

Re-injection is not always suitable: its feasibility depends upon its *displacement efficiency* (how successfully the injected fluid displaces the oil) and *sweep efficiency* (the volume of the reservoir that the injected fluid enters). Gas has a high viscosity contrast with oil, so that in reservoirs with high permeability and a combination of high dip and oil column height, the additional process of gravity segregation of the oil allows gas re-injection to produce high recovery factors.

Where reservoirs lack the vertical permeability or relief required for effective gravity segregation, operators may use a form of lateral drive called *dispersed gas re-injection*. This technique is more successful in reservoirs that are relatively thin and have little dip.

Where reservoirs have higher vertical permeability and enough vertical relief to allow the gas cap to displace the oil downwards, gas may be injected into the top of the formation or into the gas cap.

Reservoirs maintained in pressure by water are bad candidates for gas re-injection: in this case there is a danger that the cap-rock could be breached, leading to gas leakage. In

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[5] General reference bibliography for this section: H. Devold, *Oil and gas production handbook* [38]; Arthur J. Kidnay, William R. Parrish, *Fundamentals of natural gas processing* [39]; Peters M. S., Timmerhaus K. D., *Plant design and economics for chemical engineers* [40]; Global methane initiative guidelines [41]; Belli C., Chizzolini P., *Conversione dell'energia* [44]; Antaki G. A., *Piping and pipeline engineering* [45]; Al-Shalchi W., *Gas To Liquids technology* [46].

Figure 2.14: Gas pipelines system (source: Gazprom)

any case accurate geomechanical models are required to avoid risks due to this operation [47].

When re-injection is possible, gas is compressed in one or more compression trains (booster stations) due to single unit power limitations. Each train needs several intercooled stages to reach high pressures needed (gas pressure must be higher than floor well pressure, that often mean $150 bar$ or more). Compressors are driven by gas turbines or electrical motors. Reciprocating engines are used in case of small gas flows, too.

From a technical point of view, re-injection is one of the most simple alternatives to gas flaring: this operation takes place near oil wells and does not need a complex plant design. It is a good environmental solution, too, but implies no benefits in the Social dimension. Moreover, a re-injection station typically requires high capital expenditures mostly due to additional drilling operations.

After the crude has been pumped out, some gas is once again recovered, but in any case large quantities of gas remain trapped into the reservoir.

2.2.2 Pipeline transportation to markets or industrial and domestic costumers

Transportation and distribution pipelines networks are used to move gas from treating plants (figure 2.14).

Several pieces of equipments compose a pipeline system: main elements are the initial introduction station, known also as supply or inlet station; block valve stations that make possible to isolate any segment of the line for maintenance work or isolate a rupture or leak, usually located every $40-50 km$, depending on the type of pipeline; the final delivery station, known also as outlet station or terminal.

Also compression stations (boost stations) are located along the line to move the product through the pipeline: the natural gas enters the compressor station, where it is com-

Figure 2.15: LNG plant (source: Gazprom)

pressed by either a turbine, motor, or engine. Turbine compressors gain their energy by using up a small proportion of the natural gas. The turbine is coupled to a centrifugal compressor. Some compressor stations are operated by using an electric motor to turn the same type of centrifugal compressor. In this case it is required a reliable source of electricity nearby. Reciprocating natural gas engines are also used to power some compressor stations.

Pipelines transporting gas from treatment units can be connected to country's main pipeline network: in this case usually a distribution company acquires all the gas at a price settled with the producer.

Typically, gas transportation by pipeline is feasible if gas flow is about 1 billion of Sm^3 per year or more.

In case of small scale plants and/or little gas volumes, it is possible to connect near villages or industries using short pipelines networks: these costumers can purchase agreements for relatively small volumes of gas that might be difficult to market otherwise. Moreover, a small-scale direct distribution can constitute a sustainable development solution. District heating or cooling networks can be feed by natural gas, too, the gas taking the place of a more polluting fuel (such as fuel oil or coal). This is possible in particular in cold regions like Siberia.

2.2.3 Liquefied Natural Gas

Liquefied natural gas or LNG is natural gas that has been converted temporarily to liquid form for ease of storage or transport.

Liquid state natural gas transportation is possible when distances between fields and markets are large and transport via cryogenic sea vessels or cryogenic road tankers is suitable, that is where moving natural gas by pipelines is not possible or economical.

In a LNG plant (figure 2.15)one or more liquefaction trains chills natural gas to $-162°C$ at $1atm$ carrying natural gas in a liquid state.

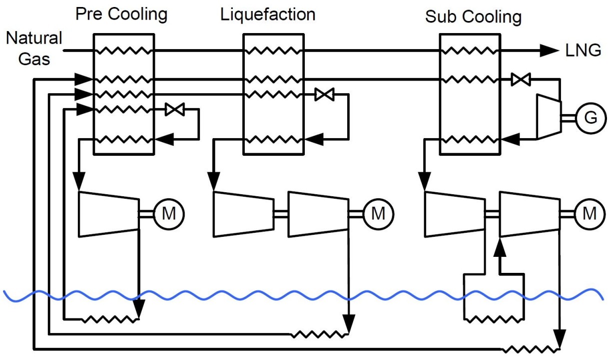

Figure 2.16: Liquefaction plant

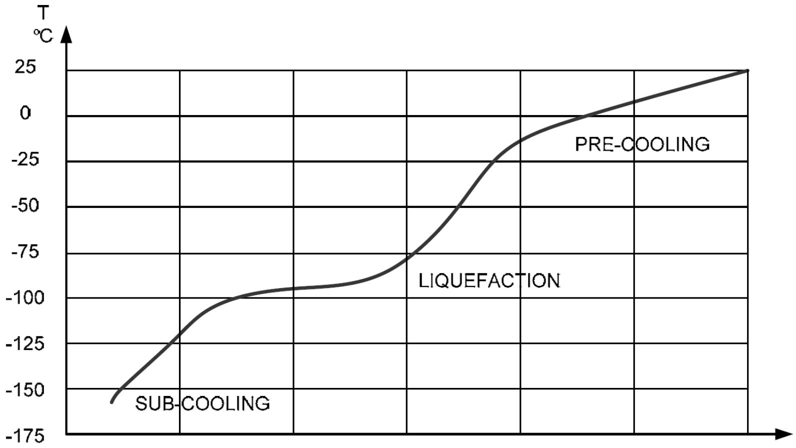

Figure 2.17: Head load to temperature gas curve

Generally, an LNG train is based on a two or three stage cooling process. A simplified three stage liquefaction plant is shown in figure 2.16. Most critical components are the heat exchangers (cold boxes) that operate at low temperatures. Gas head load to temperature curve (QT curve on figure 2.17) tends to show three distinct regions matching the pre-cooling, liquefaction and sub-coiling stages, and that is why typically three heat exchange sections are used.

Typical LNG train power use is about $28MW$ per million tons of LNG per annum.

To reach cryogenic temperatures the coolant is first passed though a compressor. Compression causes a significant temperature raise in the coolant, that exchanges heat in a water (or seawater) heat exchanger. It then goes through one or more heat exchangers (cold boxes), before it expands either through a valve or a turbo-expander causing the temperature to drop significantly. Proper liquefaction process takes the gas down from $-30°C$ to about $-125°C$ typically based on a mixture of methane and ethane and other gases. Liquefied natural gas takes up about $1/600th$ of the volume of natural gas in the gaseous state at atmospheric pressure. Because of huge CAPEX (CAPital EXpenditures) and OPEX (OPerating EXpenditures) costs, LNG plants are generally used if the amount of gas in reservoirs is at least $50-60$ billions of Sm^3.

When quantities of associated gas are small, small-scale LNG liquefaction plants[6] should be considered: their compact size enables the production of LNG close to the location of the wells and a small-scale distribution of the gas, for example by tracks. It is possible for communities without access to natural gas pipelines to install local distribution systems and have them supplied with stored LNG.

Small-scale LNG liquefaction technologies can be divided into three groups according to the thermodynamic cycle [48]:

1. Technologies based on expansion refrigeration cycles: these technologies are mostly used on peak-shaving installations and are suitable in case of very low production rates ($0.1 - 0.2 mtpa$). The refrigerant is a gas that follows a reverse Brayton cycle. Main steps are: compression-cooling (at high temperature) and expansion-heating (at low temperature); no phase change takes place, so the refrigerant fluid is gaseous all through the cycle. Refrigerant heating is used to cool down and condensate the natural gas. A single cryogenic heat exchanger is used for this step of the process. A plant of this kind is characterized by simple start & stop operations, modularity, particular compactness and typically does not makes use of flammable refrigerants. For this reasons it is a good choice in case of offshore installations. On the other hand, the major handicaps of this technology are the low efficiency, the high requirement on refrigerant fluid and the high number of rotary systems.

2. Technologies based on single mixed refrigerant cycles (without pre-cooling): the process is basically an inverse Rankine cycle with a compression-cooling-condensation stage (at high temperature) and an expansion-evaporation stage (at low temperature). The gas is chilled and liquefied in a single heat exchanger. Among all the mixed refrigerant processes, a single mixed refrigerant process provides simpler configurations of the facilities, allowing a lower CAPEX, less requirement of site area, easier start up process and lower maintenance costs, but the operation of the facilities based on this technology demand a higher cost in terms of energy consumption.

3. Technologies based on pre-cooling combined with a mixed refrigerant cycle: this technology adds a pre-cooling stage to the mixed refrigerant cycle increasing the plant efficiency. The pre-cooling stage, that usually is constituted of a reverse Rankine cycle or an absorption cycle, cools down the feed gas or condensates the mixed refrigerant.

2.2.4 Liquefied Petroleum Gas

As it was outlined in 2.1.4, if associated gas contains large fractions of heavy components (C_{2+}) a conditioning unit is required to separate these components from methane.

LPG will evaporate at ambient temperatures and pressures and is supplied in pressurised steel tanks (figure 2.18). These containers are typically filled to between 80% and 85% of their capacity to allow for thermal expansion of the contained liquid. The ratio between the volumes of the vaporized gas and the liquefied gas varies depending on composition, pressure, and temperature, but is typically around 250 : 1.

LPG can provide an alternative to other fuels or electricity in places where there are no natural gas network or electrical connections: it is useful for cooking and heating purposes but also for de-centralised electrical generation: as a matter of facts it can feed reciprocating engines producing only electricity or operating in a cogenerative asset, too.

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[6] That is plants with a production capacity between 0.1 to 2 millions of tons per annum.

Figure 2.18: LPG tanks (source: Istockphoto)

LPG is non-toxic and non-corrosive, and has a high octane rating. It burns more cleanly than petrol or fuel-oil and is especially free of the particulates from the latter. Typically, LPG has a lower heating value of $46.1 MJ/kg$ compared with $42.5 MJ/kg$ for fuel-oil, but its energy density per volume unit of $26 MJ/l$ is lower than either that of petrol or fuel-oil [49].

2.2.5 Power generation (gas to power)

A treated gas flow can feed a gas turbine power plant to obtain electrical energy (figure 2.19). Main categories of these plants are two: simple cycle or combined cycle.

Simple cycle plants (figure 2.20) have an extremely wide range in power size, from hundreds of kW in case of micro-turbines to about $200 MW$ or more in case of industrial-size turbines, and require low capital cost providing high reliability and flexibility in operation with an efficiency of about $35 - 40\%$. The maintenance of the plant is easy and maintenance costs are low among other thermal power plants. Moreover, the plant does not require heavy foundations and particular buildings.

Combined cycle plants (figure 2.21) are characterized by bigger sizes and efficiencies up to about 60% thanks to exhaust gases heat recovering in a bottom steam cycle, but in this case higher capital investments are required.

Power plants can be located faraway from treatment plants covering the distance thanks to a pipeline, but in case of small amounts of gas or flow variable in a wide range during wells lifetime (this is a typical situation in case of gas associated to oil production) also a short-chain is an interesting opportunity: it is possible to generate electricity directly into

Figure 2.19: Gas turbine power plant (source: Petrom)

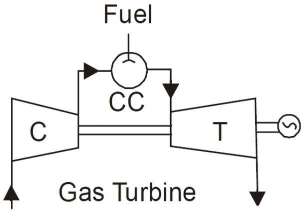

Figure 2.20: Simple cycle plant

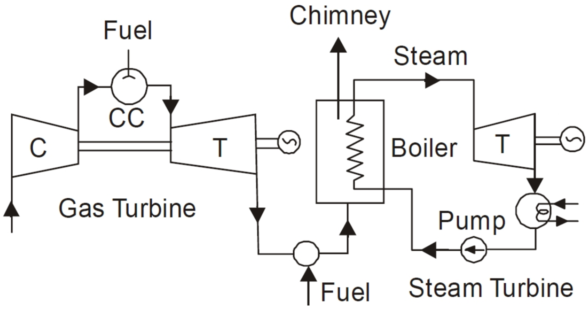

Figure 2.21: Combined cycle plant

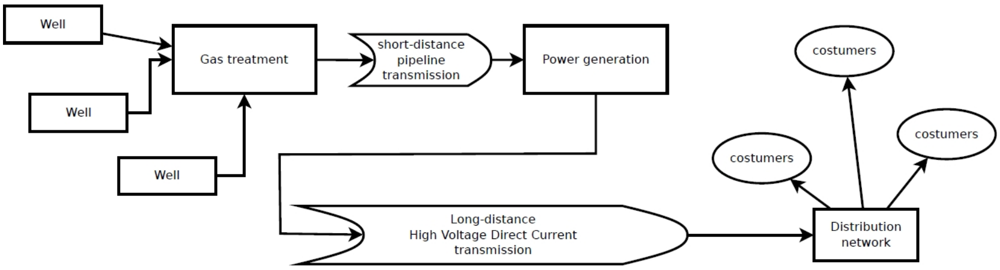

Figure 2.22: Gas To Wire chain

Figure 2.23: Gas To Liquid plant (source: Shell)

the processing plant or nearby making use of a so-called gas to wire (GTW) process[7].

Gas To Wire (figure 2.22) is a good chance for sustainable development in poor countries making possible to provide electricity to villages situated in proximity of oilfields improving their life conditions both because of the electricity and flares switching off and stimulating industrial infrastructures developing.

GTW is suitable when gas content in the reservoir is in a range from 250 millions of Sm^3 to 30 billions of Sm^3 and distances between wells and costumers are minor of $2500 - 3000 km$ [50].

Moreover, if the production takes place inside the processing plant it is possible to operate the power plant in a cogenerative arrangement making use of a part of the electricity and of the heat to feed internal processes avoiding the utilization of more pollutant fuels like heavy oil.

2.2.6 Gas To Liquid processes

Gas to liquids processes permit to convert gaseous hydrocarbons into longer-chain liquid hydrocarbons such as gasoline, diesel, methanol.

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[7] A Gas To Wire plant consists in a power plant situated nearby the wells area or the treating plant and is generally characterized by the fact that electricity is transmitted to distribution networks covering long distances by a high-voltage line operated in direct current.

Often gases are firstly converted into a syngas that is than converted into liquid synthetic fuels, but a direct conversion is possible, too.

The most common process is the Fischer-Tropsch process, that is based on intermediate syngas conversion (figure 2.23). The gas is firstly converted in a syngas composed of CO and H_2 into a reformer:

$$C_nH_m + xH_2O \to nCO + (n + m/2)H_2 \tag{2.1}$$

In particular for methane the reaction is the steam reforming reaction:

$$CH_4 + H_2O \to CO + 3H_2 \tag{2.2}$$

Usually a fired tubular reformer (FTR) is adopted[8], operating at pressures between $20bar$ and $40bar$ with outlet temperatures in the range of $815°C$ to $925°C$ with a conversion efficiency $> 95\%$ in the case of a natural gas feed.

The Fischer–Tropsch process involves a series of chemical catalyzed reactions that lead to a variety of hydrocarbons starting from the syngas obtained previously. The most important one gives alkanes as products:

$$(2n + 1)H2 + nCO \to CnH(2n + 2) + nH_2O \tag{2.3}$$

where n is a positive integer > 1.

Generally, Fischer–Tropsch process is operated in the temperature range of $150 - 300°C$ using iron-based or cobalt-based catalysts in fixed-bed tubular reactors or in slurry reactors. Temperature is a fundamental control parameter because it determines the chain length of produced hydrocarbons. Catalysts are supported on high-surface-area supports such as silica, alumina, or zeolites.

Depending on operating conditions gasoline, diesel or naphtha is obtained.

An alternative process is the conversion of the syngas to methanol, that can be used as a fuel or in chemical industry, or can be subsequently polymerized into alkanes (syn-fuels) over a zeolites catalyst (Exxon-Mobil process).

Methanol is made from syngas taking advantage of the following reactions:

$$CO + H_2O \to CO_2 + H_2\,(Water\,Gas\,Shift) \tag{2.4}$$

$$2H_2 + CO \to CH_3OH\,(Synthesis) \tag{2.5}$$

If the Mobil process is adopted, firstly methanol is dehydrated to give dimethyl-ether (DME):

$$2CH_3OH \to CH_3OCH_3 + H_2O \tag{2.6}$$

Than DME is converted to gasoline thanks to the catalyst.

In case of small or remote gas sources small GTL production units are available (Compact GTL): with a production capacity of only $1000 - 5000$ barrels per day[9] these plants can be fixed or mobile.

In particular some units can be transported by big trucks from one field to another according to the production plans (for example Alchem mobile plant, see figure 2.24).

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[8] A FTR can process up to about $250000Nm^3/h$ of gas; in case of larger quantities is possible the adoption of an autothermal reformer (ATR).

[9] Mid-size GTL plants have a production capacity between $5000bbl/day$ and $30000bbl/day$ and large-size plants have a capacity of more than $30000bbl/day$.

Figure 2.24: GTL mobile plant (source: Alchem)

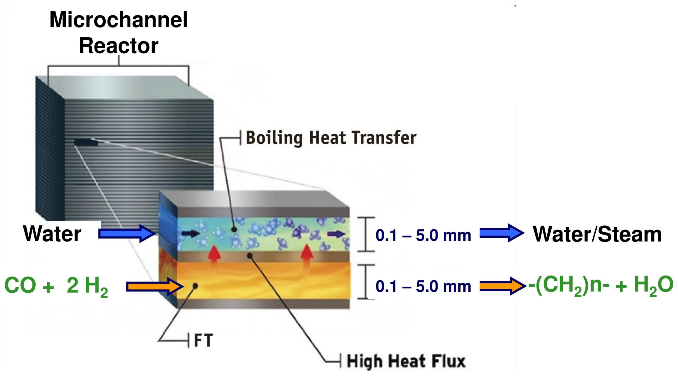

Figure 2.25: Microchannel Fischer–Tropsch reactor

These units can be hired for a certain period, especially when the capacity of the field is not big enough to install a fixed unit, and used in case of offshore fields, too.

Small-size GTL units take advantage of new technologies such as microchannel-based processes: devices using microchannel technology are characterized by parallel arrays of microchannels, with typical dimensions in the $0.1mm$ to $5.0mm$ range. Processes are accelerated 10 to 1000 fold by reducing heat and mass transfer distances, thus decreasing transfer resistance between process fluids and channel walls. System volumes can be reduced 10 fold or more compared with conventional hardware (figure 2.25). Microchannel technology is ideally suited for carrying out catalytic reactions that are either highly endothermic, such as methane reforming, or highly exothermic, such as FT synthesis [51, 52].

Membrane-based units or plasma systems are emerging, too [53].

2.2.7 Summary diagram of technologies

In this section a summary diagram of the technologies is shown to make a comparison between them clear and simple and to highlight the major strengths and weaknesses of each one. It is assumed that the energy required for various processes is obtained using a part of the associated gas. Therefore, the item *O&M* does not include energy costs.

	Reinjection	**Pipeline**	**LNG**		**LPG**	**GTW**	**GTL**	
			trad.	*small-scale*			*trad.*	*small-scale*
Volume range [bcm/y]	all	> 1	> 5	$0.1 - 1.5$	> 1	< 5	3–15	$0.001 - 0.01*$
Distances range [km]	-	all	> 3000	< 500	all	< 3000	> 1500	$< 1500*$
CAPEX	low	from inter. to high	high	low	low	low	very high	low
O&M	low	low	inter.	inter.	inter.	inter.	high	very low
Required space	very low	from inter. to high	high	low	inter.	inter.	high	from extremely to very low
Complexity of construction	low	high	high	inter.	inter.	inter.	very high	low
Complexity of O&M	low	low	inter.	inter.	inter.	inter.	high	low
Commercial experience	high	high	high	inter.	high	inter.	low	extremely low

*Only data from pilot plants available
trad. = traditional
inter. = intermediate

Part II

A multi-criteria approach to gas flaring reduction

Chapter 3

Decision methods

In the previous chapters a range of technologies that can be used to recover associated gas and avoid gas flaring were described.

However, once that it is clear what are the technologies theoretically eligible to reach the goal of eliminating or, at least, reducing the practice of associated gas flaring, to obtain the best degree of sustainability, de facto in most real situations several alternatives are possible, both in terms of configuration and physical layout of the plant and in terms of products to obtain.

Therefore, the principal problem in a first phase is almost always to choose among a more or less wide range of possible configurations, which vary depending on the specific context.

Firstly, possible configurations depend on the location of wells: some of the technologies described in the previous chapters should be omitted for purely technical reasons (e.g. because of too low gas flow rates or the inability to overcome geographical obstacles with a pipeline).

Secondly, some configurations may not be feasible because of the composition of the associated gas (for example, it is not possible to obtain significant amounts of LPG if associated gas is made up of more than 90% methane).

Moreover, the presence or absence of a local demand for gas or products such as synthetic fuels, electricity or heat makes possible or not some technological choices.

The spatial arrangement of plants is, as a rule, variable: separation, purification and eventually conversion of the gas could be carried out in the proximity of extraction wells or may take place hundreds of miles apart, depending on the distance between extraction areas and existent communication networks such as railways or roads. Plants location depends from climatic conditions, too.

For these reasons the various identified alternatives present not only different economic returns for the company but also a different impact on the environment and on social aspects for local communities.

It is therefore clear how making a choice could be very complex. To be as sustainable as possible (after verifying the feasibility of the alternatives of the project), the choice should be based on considerations relating to all the three dimensions of sustainability. Indeed, as noted earlier, the ultimate goal is to obtain recovery of associated gas choosing the best compromise among economic, environmental and social requirements.

In conclusion, because of the complexity of the problem, it could be a good solution to use a decision method, i.e. a procedure that allow a decision-maker to analyse a situation setting a series of rules in order to evaluate the alternatives and to choose the best one in accordance with the rules set before. In other words a multicriteria method, that allows to find a compromise solution considering different parameters, is necessary: as a matter of facts in a gas flaring reduction problem it is possible that an improvement of a parameter implies a worsening of another one, not necessary with a linear law.

This way is widely used both in the scientific-technological field, as done for example in [54] and in [55], and in non-scientific fields, as in [56] or in the classic example of the choice of a new car [57].

There are many different multi-criteria methods and each one is preferable in a different context. To choose the best one in a gas flaring reduction project, the main characteristic of the problem must be evaluated.

- As any other project, a gas flaring reduction project involves many partners, the stakeholders, that sometimes could be asked to express their opinion, be involved in the realization of the project or affected by the results.
- All the decision-makers should contribute to reach the solution of the problem, but each decision-maker also has objectives, criteria and principles that are different from the ones of the other decision-makers. Each decision-maker can also have a different influence towards the solution, that implies a different importance at the negotiation table.

As for indicators allowing to reach the decision, a quick look to those that will be analyzed in chapter 4 allows to make further considerations.

- Indicators can be divided in two groups: quantitative and qualitative. The latter must be evaluated somehow in order to compare them each other and combine them with quantitative indicators.
- A second issue is about quantitative indicators and their units of measurement. Being different they obviously have different dimensions, i.e. different units of measurement, so before combining them we need to make them adimensional, in order to obtain homogeneous indicators and to add them up. Many methods to make numbers dimensionless are possible, each one with his own properties and features.

These aspects allow the choice of the proper multi-criteria method for a gas flaring reduction problem.

3.1 Multi-criteria methods

Multi-criteria methods include two big families of methods: multi-objective and multi-attribute. As a simplification they can be distinguished for the purpose they have: multi-objective methods search the optimal solution of the problem optimizing a mathematical function, searching the solution in a continuous space, among infinite possible solution, whereas multi-attribute methods determine a rank among n given alternatives (a finite number of alternatives) and make the decision-maker able to choose the best one.

Both these two families of decision method can be used in a decision process in different stages of the process. It is clear that a gas flaring reduction problem, when in the phase of choosing the best project among some selected with a pre-feasibility study, has some features that make multi-attribute methods more suitable than multi-objective, principally the necessity to choose among a finite number of alternatives.

3.2 A glance over multi-attribute decision methods

Many different methods belong to multi-attribute family. The differences between them concern their approach to the problem and the kind of calculation they operate on the data.

Multi-attribute decision methods require that the decision-maker (or decision-makers) determines some fundamental elements that characterize the model [58]:

- the goal, i.e. the final and general objective to which the decision-maker strive for;
- the criteria used by the decision-maker to evaluate and compare the alternatives (possibly break down in sub-criteria);
- the alternatives themselves.

After the definition of the structure of the model, there are generally some essential steps (they will be explained better in section 3.3) [58]:

- to define the performance matrix, which sets out how each option being appraised performs on each criterion that form part of the analysis; in a performance matrix each row describes an option and each column describes the performance of the options against each criterion;
- to make a dominance analysis, that permits to exclude the alternatives that are dominated by another one (an alternative is dominant if all its indicators gain values higher or, at least, equal to those of another alternative [59]);
- to normalize the performance matrix, in order to make all the indicators dimensionless and comparable;
- to define the weights of the criteria, which helps to determine the coefficient to attribute to each criterion (the importance the criterion have in the analyzed context) in the calculation of the final score, in order to calculate the *priority matrix*;
- to rate the alternatives adding up all normalized data and assigned weight, in order to calculate a score (and a ranking) for each alternative and to assign a solution to the analyzed problem;
- to make a sensitivity analysis to verify the stability of the found solution; this analysis can be conducted on the model itself, on the criteria or on the assigned weights, so that an uncontrolled instability of the solution due to the decision-makers' subjectivity could be avoided.

Here is a short review of the most popular multi-attribute decision methods (all the following methods aggregate data using different weights for the various criteria).

Multi-attribute utility theory (MAUT) [60] Multi-attribute utility theory is a family of methods that uses functions (the value and utility functions) to describe the criteria under analysis. This MCDA approach tries to assign a utility value to each action. This utility is a number representing the preferability of the considered criterion.

This approach is very simple at first glance and it is often applied in real life. Despite its simplicity the approach presents some technical problems. The first are related to the axiomatic basis and to the construction of marginal utility functions (i.e., the utility functions relative to each single criterion), both in case of decision under deterministic and probabilistic hypotheses. MAUT often uses probabilistic analysis. The method is characterized by the difficulty of defining the necessary functions, so it is more suitable for problems with only quantitative indicators, which can at least be easily numerically estimated.

Hierarchical Analysis This method is generally used to establish a ranking of alternatives based on pairwise comparisons among all elements of a system. A hierarchical analysis method carries out a cost-benefit analysis in non-monetary terms, so that it is possible to use qualitative as well as quantitative indicators.

For further information see section 3.3.

Analysis of concordance and discordance [61] The analysis of concordance and discordance is a family of decision methods that essentially takes into account only the ranking of the alternatives considering each single criterion without considering the differences between the performance of the alternatives. Hence, it does not matter if an alternative is the best one within a criterion with a large gap or a small one compared to the second in the ranking: the matter is that the alternative is the best one. This method identifies dominance relations between the alternatives, not considering the real value of the indicators but simply giving a positive score every time an alternative is better than other considering one criterion at a time. These scores are used to build two matrices: a concordance matrix and a discordance matrix.

Elements of the concordance matrix represent the satisfaction of choosing an alternative instead of another in the considered pairwise comparison.

Elements of the discordance matrix represents the dissatisfaction of rejecting the considered alternative instead of the opposing in the pairwise comparison.

One way to consider the real distance between indicators is to use a family of variants of this analysis, the ELECTRE (ELimination Et Choix Traduisant la REalité - Elimination and choice expressing reality) family methods. These methods establish a preferability index, that is a minimum threshold for the difference between indicators beyond which the alternatives can be considered different.

Anyway, the output of an analysis of concordance and discordance could be a group of alternatives that are dominant in relation to the others, but among these alternatives the decision-maker must make a further choice.

Finally, the Promethee methods are based on pairwise comparisons. In Promethee methods the score given by the decision-maker to the alternatives is proportional to the difference between the indicators of the alternatives. The proportionality can be expressed as a mathematical function (called *preference function*). These preference functions must be chosen by the decision-makers among many possible types, and than functions must be set (generally they depend on parameters that must be fixed). The choice of the preference function and of the parameters is source of uncertainty and high subjectivity if experimental data are not available.

3.3 Analytic Hierarchy Process (AHP)

Taking into account the type of the problem considered (gas flaring reduction) and the indicators used to assess it (qualitative and quantitative ones, see chapter 4), the method that seems to have the most appropriate characteristics to make a comparison among alternatives is based on a hierarchical analysis. In particular the selected one is the *Analytic Hierarchy Process* (AHP).

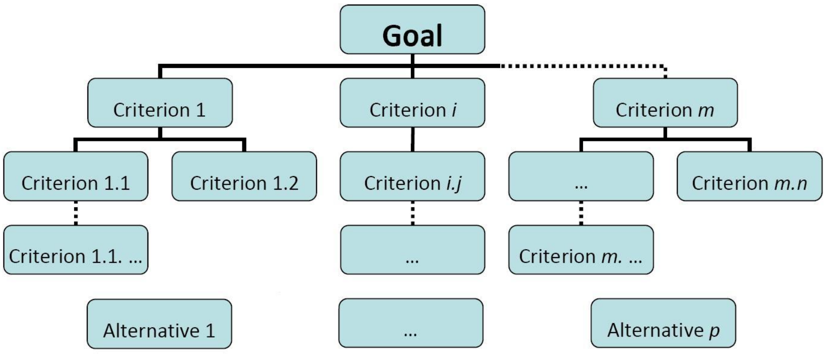

Figure 3.1: Analytic Hierarchy Process scheme

The model was developed in the 70*s* by the mathematician Saaty [62]. The decision *Process* requires the breaking down of the problem in smaller and simpler elements (hence *Analytic*) in different levels of *Hierarchy*. Saaty based the successive evaluation of alternatives on pairwise comparisons at all hierarchic levels of the problem (now broken down). Once comparisons are made, it is possible to move up the hierarchy and select the solution that best fits the goal, as shown in figure 3.1.

AHP decision model mainly consists of the following phases [58], that will be analysed in the following paragraphs:

1. hierarchical breaking down of the problem;
2. ratings of alternatives based on pairwise comparisons;
3. synthesis of the priorities and hierarchy make up;
4. consistency test;
5. sensitivity analysis;
6. negotiation and evaluation of consensus.

3.3.1 Hierarchical breaking down of the problem

The first step of an AHP analysis is to construct a decision hierarchy by breaking down the decision problem into a hierarchy of its elements.

At the top level of the hierarchy there is the goal, i.e. the objective of the decision-makers or the reason why a situation need to be solved. Possible goals could be to minimize or to maximize a certain parameter, or to find a compromise among different criteria, as previously said in section 3.2.

Another feature of the hierarchy is the criteria level: a criterion is an element to be considered in the evaluation of the problem and in the choice of the proper alternative. Each criterion can be itself broken down in other sub-criteria (or second level criteria) and so on.

A set of indicators must be used in order to evaluate the alternatives within each criterion. Each criterion could need one or more indicators, that must be carefully chosen before going on with the decision process. The indicators can be qualitative or quantitative with some difference in the calculation that will be explained later.

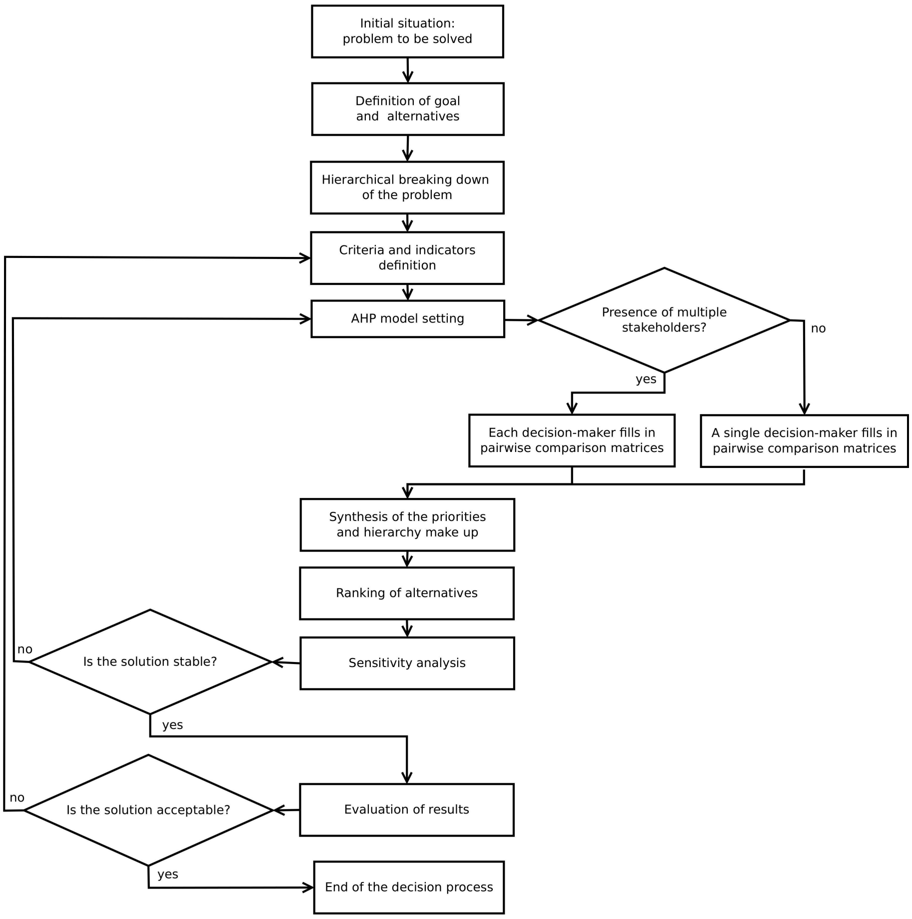

Figure 3.2: AHP flow diagram

Being possibly several stakeholders (paragraph 1.3.1 and section 3.1), each criterion and each indicator, too, could be evaluated in different ways. So these inputs must be aggregated possibly taking into account the different importance of the decision-makers. The importance of each stakeholder could be different for each criterion.

In order to better understand the process in its wholeness a complete scheme is represented in figure 3.2. A numerical example will be used hereafter to explain each step of the method. The hierarchy used in the example is explained in **BOX 1** and represented in figure 3.3.

3.3.2 Ratings based on pairwise comparisons

In AHP performance matrix is not built directly: the ratings of the different alternatives is based on pairwise comparison, that is a way to evaluate relative performance of the alternatives without considering the absolute ones (sometimes absolute performance are difficult to be estimated).

So the second step in the process is to assign a weight to each element of a level of the hierarchy, that is the relative importance that an element of the hierarchy has compared to another one. This assignment is reached on the basis of pairwise comparisons and with

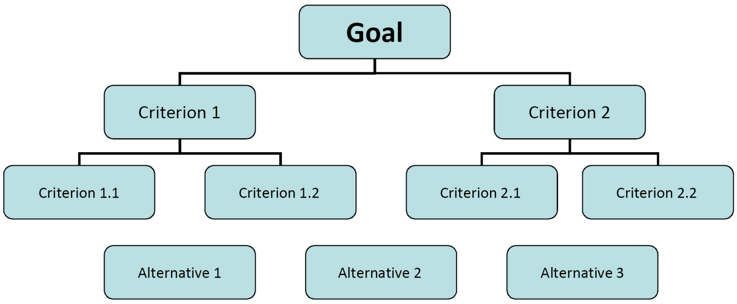

Figure 3.3: An AHP example

BOX 1

- The goal of the decision process is Goal A.
- The goal is evaluated by two first-level criteria (Criterion 1 and Criterion 2, hereafter called Crit. 1 and Crit. 2).
- The two first-level criteria are composed by two second-level criteria each one (respectively Criterion 1.1, Criterion 1.2 composing Criterion 1 and Criterion 2.1, Criterion 2.2 composing Criterion 2; second-level criteria will be called Crit 1.1, Crit 1.2, Crit 2.1 and Crit 2.2 in the next examples).
- Three alternatives (Alternative 1, Alternative 2 and Alternative 3, hereafter Alt. 1, Alt. 2 and Alt. 3) are selected and evaluated by the decision-makers in order to reach the goal.

The hierarchy will be used throughout this chapter, also with numerical examples of the evaluations of the alternatives for the several criteria. In the example there will be only one decision-maker instead of many of them. How to consider the presence of multiple decision-makers will be shown at the end of the chapter.

the construction of a number of matrices.

There are three groups of matrices: in the first one there are matrices that compare all the alternatives each other within a bottom-level criterion (a bottom-level criterion is a criterion that estimates or measures the performance of each alternative using one or more indicators); in the second group there are matrices that compares two elements of the same level of the hierarchy referring to the same element of the upper level (i.e. the second-level Criterion 1.1 in figure 3.3 can be compared only with the second-level Criterion 1.2 within the first-level Criterion 1); in the last groups there is only one matrix that evaluates the importance of each first-level criterion within the goal.

To make each pairwise comparison the fundamental scale of Saaty is used [63]. The scale is based on numbers from 1 to 9, where 1 indicates that the two elements compared have the same importance for the criterion considered and 9 indicates that the first element have extremely better performances than the second one, as shown in table 3.1. If the first element is less important than the second, a number between $1/9$ and 1 is used.

Saaty's scale can be directly used in qualitative comparisons, that are the comparisons at all levels of the hierarchy except the bottom one, where indicators are used to measure

Table 3.1: The fundamental Saaty's scale of absolute numbers

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favour one activity over another
4	Moderate or plus	
5	Strong importance	Experience and judgment strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

the performance of the alternatives within a criterion.

The pairwise comparison matrix about a generic criterion A will be indicated as the following:

$$[\mathbf{A}] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & a_{ij} & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \tag{3.1}$$

where a_{ij} represent the comparison of element i with element j.

Each pairwise comparison matrix must necessarily have 1 as an element of the main diagonal (both for qualitative indicators and for quantitative indicators), because each element of the hierarchy or each alternative has the equal importance than itself; each matrix must also be reciprocal (for example, in (3.5) the element $a_{12} = {}^{I_1}/_{I_2}$ is the reciprocal of the element $a_{21} = {}^{I_2}/_{I_1}$):

$$a_{ij} = \frac{1}{a_{ji}} \tag{3.2}$$

In next paragraphs it is shown how to make comparisons for the different kind of indicators.

BOX 2
The indicator that evaluate Criterion 1.2 is qualitative and it is used to build the pairwise comparison matrix of the Criterion 1.2 in (3.4):

$$\begin{array}{c|ccc} \text{Crit. 1.2} & \text{Alt. 1} & \text{Alt. 2} & \text{Alt. 3} \\ \hline \text{Alt. 1} & 1 & 6 & 2 \\ \text{Alt. 2} & 1/6 & 1 & 1/4 \\ \text{Alt. 3} & 1/2 & 4 & 1 \end{array} \rightarrow \begin{bmatrix} 1 & 6 & 2 \\ 1/6 & 1 & 1/4 \\ 1/2 & 4 & 1 \end{bmatrix} \tag{3.4}$$

The meaning of (3.4) is that the performance of Alternative 3 within Criterion 1.2 (measured by a qualitative indicator) is *moderately more important* (or moderately better) than the performance of Alternative 2

Qualitative indicators make possible for the decision-makers the comparisons between the different alternatives, as shown in (3.3):

$$\begin{array}{c|ccc} \text{Crit. 1} & \text{Alt. 1} & \dots & \text{Alt. } m \\ \hline \text{Alt. 1} & 1 & \dots & \text{Alt. 1 vs Alt. } m \\ \vdots & \vdots & \text{Alt. } i\text{vs Alt. } j & \vdots \\ \text{Alt. } m & \text{Alt. } m\text{vs Alt. 1} & \dots & 1 \end{array} \rightarrow$$

$$\rightarrow \begin{bmatrix} 1 & \dots & \text{Alt. 1 vs Alt. } m \\ \vdots & \text{Alt. } i\text{vs Alt. } j & \vdots \\ \text{Alt. } m\text{vs Alt. 1} & \dots & 1 \end{bmatrix} \tag{3.3}$$

Each comparison is made thinking if an alternative has better performance than another one within a criterion and how much this is important. The comparisons are affected by the judgments and points of view of the decision-makers. An example of comparison for qualitative indicator is given in **BOX 2.**

Quantitative indicators must be normalized before the pairwise comparisons, in order to make them dimensionless and comparable. The normalization is made in the range of Saaty's scale, from 1 to 9, so that 1 means the worst performance among the alternatives and 9 indicates the best one. Intermediate values indicates intermediate performances with a linear trend. Obviously if the indicator is a benefit 9 will correspond to the highest value, whereas is the indicator is a cost 9 will correspond to the lowest value. Finally the elements a_{ij} of the pairwise comparison matrix $[\mathbf{A}]$ are the ratio between two normalized indicators I_i e I_j for alternatives i and j, as shown in (3.5):

$$\begin{array}{c|ccc} \text{Crit. 2} & \text{Alt. 1} & \text{Alt. 2} & \text{Alt. 3} \\ \hline \text{Alt. 1} & 1 & I_1/I_2 & I_1/I_3 \\ \text{Alt. 2} & I_2/I_1 & 1 & I_2/I_3 \\ \text{Alt. 3} & I_3/I_1 & I_3/I_2 & 1 \end{array} \rightarrow \begin{bmatrix} 1 & I_1/I_2 & I_1/I_3 \\ I_2/I_1 & 1 & I_2/I_3 \\ I_3/I_1 & I_3/I_2 & 1 \end{bmatrix} \tag{3.5}$$

where the vector of quantitative normalized indicators evaluating the performance of each alternative within a bottom level criterion is:

$$\mathbf{I} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{3.6}$$

BOX 3

The indicator evaluating Criterion 1.1 is quantitative; the values of the indicator for each alternatives are shown by the vector in (3.7) and its corresponding normalized vector in (3.8)

$$\begin{bmatrix} I1_{\text{Alt. 1}} \\ I1_{\text{Alt. 2}} \\ I1_{\text{Alt. 3}} \end{bmatrix} = \begin{bmatrix} 54.5 \\ 107 \\ 23 \end{bmatrix} \tag{3.7}$$

$$\begin{bmatrix} I1_{\text{norm\_Alt. 1}} \\ I1_{\text{norm\_Alt. 2}} \\ I1_{\text{norm\_Alt. 3}} \end{bmatrix} = \begin{bmatrix} 4 \\ 9 \\ 1 \end{bmatrix} \tag{3.8}$$

Normalized vector is then used in (3.9) to build the pairwise comparison matrix of the Criterion 1.1:

$$\begin{array}{c|ccc} \text{Crit. 1.1} & \text{Alt. 1} & \text{Alt. 2} & \text{Alt. 3} \\ \hline \text{Alt. 1} & 1 & 4/9 & 4/1 \\ \text{Alt. 2} & 9/4 & 1 & 9/1 \\ \text{Alt. 3} & 1/4 & 1/9 & 1 \end{array} \rightarrow \begin{bmatrix} 1 & 4/9 & 4/1 \\ 9/4 & 1 & 9/1 \\ 1/4 & 1/9 & 1 \end{bmatrix} \tag{3.9}$$

In (3.9) it is shown that relative performance in a quantitative indicator like the one used for Criterion 1.1 are given by the ratio between the normalized indicators themselves.

An example of comparison for qualitative indicator is given in **BOX 3.**

In **BOX 4** there is a summary of the matrices obtained in the example.

3.3.3 Synthesis of the priorities and hierarchy building

Once obtained the pairwise comparisons matrices it is necessary to calculate the *priority vectors*. First of all it is therefore necessary to establish how such vectors should be obtained. This can be done considering that the vector must fulfil some basic conditions.

First of all, a priority vector should express the numerical ranking of the alternatives, that indicates an order of preference among them. So priorities of the alternatives (or of the other elements of the hierarchy) should be the weights, i.e. the importance the element has within the considered criterion, or the importance a criterion has within the goal. As a matter of facts, according to Saaty [64], the order given by a priority vector should reflect the cardinal preference indicated by the pairwise comparisons.

A direct consequence of this fact from a mathematical point of view is that a priority vector should be a vector that is unique to within a positive multiplicative constant c (a similarity transformation).

Secondly, as it will be more clear at the end of this paragraph, it should be considered that AHP uses a principle of hierarchic composition: the priorities of each alternative within multiple criteria are obtained multiplying each priority of an alternative by the priority of its corresponding criterion and adding over all the criteria to obtain the overall priority of that alternative. This means that at the end of this process a new priority vector is obtained. This vector could itself be combined with other ones to get another priority vector referring to the upper level of the hierarchy, and so on.

BOX 4

- One matrix for the pairwise comparisons of the first-level criteria (Criterion 1 and Criterion 2 in figure 3.3) within the goal is obtained, as shown in (3.10):

$$\begin{array}{c|cc} \text{Goal A} & \text{Crit. 1} & \text{Crit. 2} \\ \hline \text{Crit. 1} & 1 & 3 \\ \text{Crit. 2} & 1/3 & 1 \end{array} \rightarrow \begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix} \tag{3.10}$$

  The meaning of the pairwise comparison between Criterion 1 and Criterion 2 is that Criterion 1 has a *moderate importance* compared to Criterion 2 referring to the Saaty's scale;

- two matrices for the pairwise comparison of the second-level criteria to their reference first-level criterion (i.e. Criterion 1.1 are compared with Criterion 1.2 to established their importance within Criterion 1, the same procedure is followed for Criteria 2.1 and 2.2 within Criterion 2). An example of this kind of matrix is given in (3.11):

$$\begin{array}{c|cc} \text{Crit. 2} & \text{Crit. 2.1} & \text{Crit. 2.2} \\ \hline \text{Crit. 2.1} & 1 & 1/5 \\ \text{Crit. 2.2} & 5 & 1 \end{array} \rightarrow \begin{bmatrix} 1 & 1/5 \\ 5 & 1 \end{bmatrix} \tag{3.11}$$

  that means that Criterion 2.2 is *strongly more important* than Criterion 2.1 within Criterion 2;

- four matrices to compare the different alternatives within each second-level criterion (e.g. alternative 1, alternative 2 and alternative 3 are compared to establish the performance and ranking of the alternatives according to the criterion 1.2).

Therefore, a priority vector must reproduce itself on a ratio scale because it is ratios that preserve the strength of preferences expressed by pairwise comparisons.

Hence, a second necessary condition is that a priority vector must be invariant under hierarchic composition for its own judgment matrix.

These two conditions together lead to the conclusion that a priority vector $\mathbf{w}$ should fulfil the following:

$$[\mathbf{A}] \cdot \mathbf{w} = c \cdot \mathbf{w}, c > 0 \tag{3.12}$$

Whereas pairwise comparison matrices are positive and reciprocal, this is a special case of the following [64]:

Theorem. *For a given positive matrix* $[A]$*, the only positive vector* $\mathbf{x}$ *and only positive constant* c *that satisfy* $[\mathbf{A}] \cdot \mathbf{w} = c \cdot \mathbf{w}$ *is a vector* $\mathbf{x}$ *that is a positive multiple of the Perron vector (principal eigenvector) of* $[A]$*, and the only such* c *is the Perron value (principal eigenvalue) of* $[A]$*.*

Proof. Lets consider $\mathbf{z}$ as a positive left eigenvector of $[A]$ corresponding to the Perron value, whose algebraic multiplicity is one. Suppose there is a positive vector $\mathbf{y}$ and a positive scalar d such that $[\mathbf{A}] \cdot \mathbf{y} = d \cdot \mathbf{y}$. If d and c are not equal, then by biorthogonality $\mathbf{y}$ is orthogonal to $\mathbf{z}$, which is impossible since both vectors are positive. If d and c are equal, then **y** and **x** are dependent since c has algebraic multiplicity one, and **y** is a positive multiple of **x**. □

In conclusion, going back to the specific case of AHP, the priority vector of each pairwise comparison matrix is well represented by the principal eigenvector of the matrix itself [65, 64]:

$$[\mathbf{A}] \cdot \mathbf{w} = \lambda_{max} \cdot \mathbf{w} \tag{3.13}$$

where $[\mathbf{A}]$ is the pairwise comparisons matrix (3.1),λ_{max} is the largest eigenvalue (the principal eigenvalue) of $[\mathbf{A}]$ and $\mathbf{w}$ is the principal eigenvector associated to λ_{max}, as shown in (3.14):

$$\mathbf{w} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{3.14}$$

A common practice to avoid the calculation of the eigenvector is to use the geometric mean method[1] [67, 66].

In the case of this method the components of vector **w** are the geometric means of the rows of matrix $[\mathbf{A}]$ as shown in (3.15):

$$w_i = \sqrt[n]{a_{i1} \cdot a_{i2} \cdot \ldots \cdot a_{in}} \tag{3.15}$$

so that **w** is obtained as in (3.16):

$$\mathbf{w} = \begin{bmatrix} \sqrt[n]{a_{11} \cdot a_{12} \cdot \ldots \cdot a_{1n}} \\ \sqrt[n]{a_{21} \cdot a_{22} \cdot \ldots \cdot a_{2n}} \\ \ldots \\ \sqrt[n]{a_{i1} \cdot a_{i2} \cdot \ldots \cdot a_{in}} \\ \ldots \\ \sqrt[n]{a_{n1} \cdot a_{n2} \cdot \ldots \cdot a_{nn}} \end{bmatrix} \tag{3.16}$$

Vector **w** can now be normalized so that the sum of its elements is 1, obtaining the normalized priority vector **x** (3.14):

$$\mathbf{x} = \begin{bmatrix} \frac{w_1}{S} \\ \frac{w_2}{S} \\ \vdots \\ \frac{w_n}{S} \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \tag{3.17}$$

where

$$S = \sum_{i=1}^{n} w_i \tag{3.18}$$

In alternative, normalized priority vector of a quantitative indicator could be obtained with a normalization of the indicators vector (as the one in (3.8)) so that the sum of its elements is 1, as shown in **BOX 6.**

---

[1] It should be noticed that the method of derivation of priority vector could seriously affect only very close priorities, falling into the range of uncertainty explained in paragraph 4.1 [66]. In particular, results obtained with the eigenvector method and the geomean method should not differ by more than 10% except in very special cases (a comparison example is given in the next chapter, table 4.2).

BOX 5

Referring to (3.3), a matrix about the qualitative Criterion 1.2 can be built, as shown in (3.19) extracting values from the (3.4):

$$[\mathbf{A}_{C1.2}] = \begin{bmatrix} 1 & 6 & 2 \\ 1/6 & 1 & 1/4 \\ 1/2 & 4 & 1 \end{bmatrix} \tag{3.19}$$

The calculation procedure is as follows:

$$w_1 = \sqrt[3]{1 \cdot 6 \cdot 2} \tag{3.20}$$

$$w_2 = \sqrt[3]{1/6 \cdot 1 \cdot 1/4} \tag{3.21}$$

$$w_3 = \sqrt[3]{1/2 \cdot 4 \cdot 1} \tag{3.22}$$

$$\mathbf{w}_{C1.2} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} 2.289 \\ 0.347 \\ 1.260 \end{bmatrix} \tag{3.23}$$

$$S = 2.289 + 0.347 + 1.260 = 3.896 \tag{3.24}$$

$$\mathbf{x}_{C1.2} = \begin{bmatrix} 0.588 \\ 0.089 \\ 0.323 \end{bmatrix} \tag{3.25}$$

For Criterion 1.1, expressed by a quantitative indicator, the matrix $[\mathbf{A}_{C1.1}]$, extracted from the (3.9), is shown in (3.26):

$$[\mathbf{A}_{C1.1}] = \begin{bmatrix} 1 & 4/9 & 4/1 \\ 9/4 & 1 & 9/1 \\ 1/4 & 1/9 & 1 \end{bmatrix} \tag{3.26}$$

The related principal eigenvector $\mathbf{w}_{C1.1}$ in (3.30) is calculated as previously explained and as shown as following:

$$w_1 = \sqrt[3]{1 \cdot 4/9 \cdot 4/1} \tag{3.27}$$

$$w_2 = \sqrt[3]{9/4 \cdot 1 \cdot 9/1} \tag{3.28}$$

$$w_3 = \sqrt[3]{1/4 \cdot 1/9 \cdot 1} \tag{3.29}$$

$$\mathbf{w}_{C1.1} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} 1.211 \\ 2.726 \\ 0.303 \end{bmatrix} \tag{3.30}$$

and the normalized priority vector is shown in (3.31):

$$\mathbf{x}_{C1.1} = \begin{bmatrix} 0.286 \\ 0.643 \\ 0.071 \end{bmatrix} \tag{3.31}$$

with the sum of its components in (3.32):

$$S = 1.211 + 2.726 + 0.303 = 4.240 \tag{3.32}$$

BOX 6

$$\begin{bmatrix} \text{I1}_{\text{norm\_Alternative 1}} \\ \text{I1}_{\text{norm\_Alternative 2}} \\ \text{I1}_{\text{norm\_Alternative 3}} \end{bmatrix} = \begin{bmatrix} 4 \\ 9 \\ 1 \end{bmatrix} \tag{3.33}$$

$$S = \sum_i \text{I1}_{\text{norm\_Alternative } i} = 4 + 9 + 1 = 14 \tag{3.34}$$

$$\mathbf{x}_{C1.1} = \begin{bmatrix} 4/14 \\ 9/14 \\ 1/14 \end{bmatrix} = \begin{bmatrix} 0.286 \\ 0.643 \\ 0.071 \end{bmatrix} \tag{3.35}$$

In (3.35) the same vector in (3.31) is obtained.

At the end one normalized priority vector for each matrix of the hierarchy is obtained. In particular there are:

- a vector that express the priority of the first-level criteria within the goal;
- some vectors that express the priority of the any-level criteria within their upper-level criteria;
- some vectors that express the priority of the alternatives within the bottom-level criteria;
- some vectors that express the influence of the decision-makers within each criterion.

A list of priority vectors for the example is given in **BOX 7**.

To operate the final choice it is necessary to aggregate all the priority vectors obtained in the previous step:

1. some matrices must be built by placing side by side all priority vectors evaluating the alternatives within the bottom-level criteria, as in (3.43):

$$[\mathbf{X}_{C1.X}] = \begin{bmatrix} x1_{C1.1} & x1_{C1.2} & \cdots & x1_{C1.m} \\ x2_{C1.1} & x2_{C1.2} & \cdots & x2_{C1.m} \\ \vdots & \vdots & xi_{C1.j} & \vdots \\ xn_{C1.1} & xn_{C1.2} & \cdots & xn_{C1.m} \end{bmatrix} \tag{3.43}$$

   where $xi_{C1.j}$ is the i-th of the n element of the priority vector of the j-th of the m second-level criterion within Criterion 1; these matrices are similar to the performance matrices introduced in (3.2); hereafter these matrices will be called partial performance matrices;

2. all these partial performance matrices must be multiplied by the priority vector of the upper-level criterion, obtaining some new vectors that give the priority of the alternatives within the upper-level criterion, that once placed side by side they make up the partial performance matrix $\mathbf{x}_{CX}$ in (3.44)

$$[\mathbf{X}_{CX}] = \begin{bmatrix} x1_{C1} & x1_{C2} & \cdots & x1_{Cm} \\ x2_{C1} & x2_{C2} & \cdots & x2_{Cm} \\ \vdots & \vdots & xi_{Cj} & \vdots \\ xn_{C1} & xn_{C2} & \cdots & xn_{Cm} \end{bmatrix} \tag{3.44}$$

BOX 7
In the example of this chapter, seven vectors are obtained:

- a vector referred to the goal, in (3.36):

$$\mathbf{x}_{Goal} = \begin{bmatrix} 0.750 \\ 0.250 \end{bmatrix} \tag{3.36}$$

- two vectors referred to the second-level criteria within first-level criteria, in (3.37) and (3.38):

$$\mathbf{x}_{C1} = \begin{bmatrix} 0.667 \\ 0.333 \end{bmatrix} \tag{3.37}$$

$$\mathbf{x}_{C2} = \begin{bmatrix} 0.167 \\ 0.833 \end{bmatrix} \tag{3.38}$$

- four vectors referred to the alternatives within the bottom criteria ($\mathbf{x}_{C1.1}$ and $\mathbf{x}_{C1.2}$ in (3.39) and (3.40) for the second-level criteria within Criterion 1, $\mathbf{x}_{C2.1}$ and $\mathbf{x}_{C2.2}$ in (3.41) and (3.42) for the second-level criteria within Criterion 2):

$$\mathbf{x}_{C1.1} = \begin{bmatrix} 0.286 \\ 0.643 \\ 0.071 \end{bmatrix} \tag{3.39}$$

$$\mathbf{x}_{C1.2} = \begin{bmatrix} 0.588 \\ 0.089 \\ 0.323 \end{bmatrix} \tag{3.40}$$

$$\mathbf{x}_{C2.1} = \begin{bmatrix} 0.819 \\ 0.091 \\ 0.091 \end{bmatrix} \tag{3.41}$$

$$\mathbf{x}_{C2.2} = \begin{bmatrix} 0.083 \\ 0.333 \\ 0.583 \end{bmatrix} \tag{3.42}$$

where $x_{i_{Cj}}$ is the i-th of the n element of the priority vector of the j-th of the m lower-level criterion within upper-level criterion;

3. steps 1 and 2 are repeated for each level of the hierarchy;

4. at the last level of the hierarchy the goal is reached and the last vector obtained is the global priority vector $\mathbf{x}_{Alternatives}$ in (3.45):

$$\mathbf{x}_{Alternatives} = \begin{bmatrix} x_{A1} \\ x_{A2} \\ \vdots \\ x_{An} \end{bmatrix} \tag{3.45}$$

where x_{Ai} is the global priority of the i-th alternative within the goal.

It is immediate to establish a rank among the alternatives starting from the vector $\mathbf{x}_{Alternatives}$: the first choice is the alternative with the higher x_{Ai} and so on. The value of x_{Ai} is always between 0 and 1. If x_{Ai} is multiplied by 100 it could be interpreted as the preference that the model assigns to the i-th alternative as a percentage. The more x_{Ai} is higher, the more the alternative i should be better than the other analyzed.

The conclusion of the example of the chapter, with the calculation of the global priority vector, is given in **BOX 8**.

In the case of the presence of a plurality of decision-makers there are some differences with the procedure presented in this chapter:

- each decision-maker must fill in the pairwise comparison matrices used in the hierarchy;
- a priority vector (derived by a pairwise comparison matrix) must be created in order to give a weight to each decision-maker;
- this vector must be used to combine the matrices compiled by the different decision-makers so that the procedure presented in this chapter can be used.

A numerical example of a problem with the presence of many decision-makers is given in **BOX 9**.

3.3.4 Consistency test

The fourth step is to determine whether the input data satisfies a consistency test. The test is important in order to be sure that all the data used in the pairwise comparisons matrices are coherent and sensible. This obviously concerns qualitative comparisons that must respect some logical rules as principles of transitivity and reciprocity. However it is possible that decision-makers can not easily fill in the matrices in a reliable way, so the consistency test is a tool that helps decision-makers to check if they made comparisons properly.

The transitivity principle is expressed in (3.57):

$$if\; A > B\; and\; B > C \Longrightarrow A \gg C \tag{3.57}$$

that means that if element A is considered better then element B and element B is considered better then element C, then element A must be much better then element C.

For further explanation see **BOX 10**.

BOX 8

The following matrices within the first-level criteria are obtained (partial performance matrix $\mathbf{X}_{C1.X}$ in (3.46) placing side by side vectors $\mathbf{X}_{C1.1}$ in (3.39) and $\mathbf{X}_{C1.2}$ in (3.40), and partial performance matrix $\mathbf{X}_{C2.X}$ in (3.47) from vectors $\mathbf{X}_{C2.1}$ in (3.41) and $\mathbf{X}_{C2.2}$ in (3.42)):

$$\mathbf{X}_{C1.X} = \begin{bmatrix} 0.286 & 0.588 \\ 0.643 & 0.089 \\ 0.071 & 0.323 \end{bmatrix} \tag{3.46}$$

$$\mathbf{X}_{C2.X} = \begin{bmatrix} 0.819 & 0.083 \\ 0.091 & 0.333 \\ 0.091 & 0.583 \end{bmatrix} \tag{3.47}$$

Then, multiplying (3.46) and (3.47) by the priority vectors of the second-level criterion, $\mathbf{x}_{C1}$ in (3.37) and $\mathbf{x}_{C2}$ in (3.38), and placing them side by side allow to obtain partial performance matrix $\mathbf{X}_{CX}$ as shown in (3.48):

$$\mathbf{X}_{CX} = \begin{bmatrix} 0.387 & 0.206 \\ 0.458 & 0.293 \\ 0.155 & 0.501 \end{bmatrix} \tag{3.48}$$

and multiplying again by the priority of the first-level criteria within the goal allows to obtain $\mathbf{x}_{Alternatives}$ in (3.49):

$$\mathbf{x}_{Alternatives} = \begin{bmatrix} 0.341 \\ 0.417 \\ 0.242 \end{bmatrix} \tag{3.49}$$

that represents the solution of the problem. In this example the alternative that should be preferred (in according to the pairwise comparisons made before) is the second one, followed by the first and the third as the worst alternative.

The *Consistency Index CI* shown in (3.60), that measures the level of incoherence of the matrix, is used to check the matrices:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.60}$$

where λ_{max} is the maximum eigenvalue of the matrix and n is its rank. The perfect consistency is obtained when $CI = 0$, that happens when λ_{max} is equal to the rank of the matrix, whereas it grows as λ_{max} grows. As a matter of facts, it is possible to demonstrate [64] that a positive reciprocal matrix $[\mathbf{A}]$ has $\lambda_{max} \geq n$, with equality if and only if $[\mathbf{A}]$ is perfectly consistent.

As an alternative, if the method of the geometric mean was used and therefore λ_{max} had not been evaluated, it is possible to adopt the following procedure to evaluate a Consistency Index:

1. multiplying priority vector $\mathbf{x}$ (paragraph 3.3.3) by its pairwise comparisons matrix $[\mathbf{A}]$, obtaining a new vector, $\mathbf{y}$:

$$[\mathbf{A}] \cdot \mathbf{x} = \mathbf{y} \tag{3.61}$$

BOX 9

Assuming the presence of two decision-makers:

- comparison matrix to determine the weights of the decision-makers $D1$ and $D2$ is

$$\begin{array}{c|cc} \text{Decision-makers} & D1 & D2 \\ \hline D1 & 1 & 4 \\ D2 & 1/4 & 1 \end{array} \rightarrow \begin{bmatrix} 1 & 4 \\ 1/4 & 1 \end{bmatrix} \tag{3.50}$$

- priority vector of matrix in (3.50) is the following vector:

$$\mathbf{x}_{Decision-makers} = \begin{bmatrix} 0.800 \\ 0.200 \end{bmatrix} \tag{3.51}$$

- pairwise comparison matrices are separately compiled by each decision-maker, so that a pair of matrices is obtained instead of each one of the previous example, as shown in (3.52) and (3.53):

$$\left[\mathbf{A}^{D1}_{C1.2}\right] = \begin{bmatrix} 1 & 2 & 1/6 \\ 1/2 & 1 & 1/7 \\ 6 & 7 & 1 \end{bmatrix} \tag{3.52}$$

$$\left[\mathbf{A}^{D2}_{C1.2}\right] = \begin{bmatrix} 1 & 1/3 & 4 \\ 3 & 1 & 8 \\ 1/4 & 1/8 & 1 \end{bmatrix} \tag{3.53}$$

- priority vectors of matrices compiled by decision-makers are the following ones:

$$\mathbf{x}^{D1}_{C1.2} = \begin{bmatrix} 0.151 \\ 0.091 \\ 0.758 \end{bmatrix} \tag{3.54}$$

$$\mathbf{x}^{D2}_{C1.2} = \begin{bmatrix} 0.256 \\ 0.671 \\ 0.073 \end{bmatrix} \tag{3.55}$$

- with the combining of vectors $\mathbf{x}^{D1}_{C1.2}$ and $\mathbf{x}^{D2}_{C1.2}$ a priority vector about Criterion 1.2 is obtained and it can be used in the method as shown in the previous example:

$$\mathbf{x}^{All}_{C1.2}(i) = \sum_j \mathbf{x}^{Dj}_{C1.2}(i) * \mathbf{x}_{Decision-makers}(j) \rightarrow \begin{bmatrix} 0.172 \\ 0.207 \\ 0.621 \end{bmatrix} \tag{3.56}$$

BOX 10

Matrix (3.4) was an example of a consistent matrix, and the previous relationships corresponds to the following relationships between elements of the matrix:

$$a_{13} > 1 \, and \, a_{32} > 1 \implies a_{12} \gg 1 \tag{3.58}$$

If the comparisons between $\mathrm{I1}_{\mathrm{norm\_Alt\ 1}}$ and $\mathrm{I1}_{\mathrm{norm\_Alt\ 3}}$ (and the corresponding elements a_{23} and a_{32}) are modified as in (3.59)

$$[\mathbf{A}^*_{C1.2}] = \begin{bmatrix} 1 & 6 & 1/8 \\ 1/6 & 1 & 1/4 \\ 8 & 4 & 1 \end{bmatrix} \tag{3.59}$$

the matrix becomes inconsistent.

Table 3.2: *RI* experimentally calculated by Saaty

Matrix rank (n)	1	2	3	4	5	6	7	8	9	10
Random Index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2. dividing each component of $\mathbf{y}$ by its equivalent component of $\mathbf{x}$:

$$\mathbf{z} = \begin{bmatrix} \frac{y_1}{x_1} \\ \frac{y_2}{x_2} \\ \vdots \\ \frac{y_n}{x_n} \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix} \tag{3.62}$$

3. adding together the components of $\mathbf{z}$ and divide the sum by the rank of the matrix:

$$\widetilde{\lambda}_{max} = \frac{(z_1 + z_2 + \ldots + z_n)}{n} \tag{3.63}$$

4. evaluating CI using $\widetilde{\lambda}_{max}$ instead of λ_{max}:

$$CI \simeq \frac{\widetilde{\lambda}_{max} - n}{n-1} \tag{3.64}$$

In any case, the last step of consistency check is to calculate the *Consistency Ratio* (CR), that is the ratio of CI to the *Random Index* (RI) for the same order of the matrix, as in (3.65):

$$CR = \frac{CI}{RI_n} \tag{3.65}$$

Random Indices are average consistency indices obtained as the mean of CI of hundreds randomly generated reciprocal square matrices (in table 3.2 the Random Indices calculated by Saaty [62] for ranks from 1 to 10).

To consider reliable a matrix (and the judgment related) is preferable to have a CR less than 0.10. If CR is greater than 0.10 then the consistency test fails. This means that the result is not totally reliable for the AHP analysis, therefore it is suggested to check the numbers inserted in the matrix.

There are also many mechanical and automatic methods to improve consistency of a matrix, as the ones in [64] and in [68].

The consistency test for the matrices used in the example of the chapter is shown in **BOX 11**, and an example of non consistency matrix is given in **BOX 12**.

3.3.5 Sensitivity analysis

The last step required by the method is the sensitivity analysis.

Requiring many input data in the first step of the process, AHP is affected by the subjectivity of the decision-makers which usually have different objectives and points of view [58]. To prevent this from influencing excessively the decision process it is important to verify the stability of the solution with a sensitivity analysis as just said.

Different sensitivity analysis are possible for an AHP, with particular attention to the degrees of freedom used by the decision-makers.

In a hierarchy like the one in figure 3.1 different simulations can be performed, the preliminary ones are listed hereafter:

- by varying in a limited range the weights assigned to criteria and sub-criteria,
- by varying the weight assigned to the different decision-makers
- by formulating different "what-if" scenarios in order to verify the possible presence of an element of the hierarchy that can influence the final or a partial result too much at each level of the hierarchy.

For a more detailed sensitivity analysis there are many possibility analysed in many researches and articles as in [69] and in [70].

If the result of AHP, i.e. the rank established by the global priority vector, remains the same during the sensitivity analysis, it means that the solution is stable and reliable in the range considered, otherwise the solution strictly depends on the decision of the stakeholders and a review of the model or of the comparisons is suggested.

It is obvious that if there are two or more decision-makers consistency tests and sensitivity analysis must be conducted also on the weights and the judgments of the decision-makers.

3.3.6 Negotiation and evaluation of consensus

When many stakeholders participate to the decision process, i.e. when there are multiple decision-makers, the solution given by the decision process could not be shared by all of them, so that a phase of evaluation of their consensus is necessary and this might imply a “negotiation” between them [71]. This phase is important to understand why the proposed solution seems to be winner against the others and to reach an agreement regarding the proposed solution by negotiating and exchanging ideas.

3.4 Limits and strengths of the model

AHP has obviously some weaknesses. The limits of the model are well known and have been studied thoroughly [58].

BOX 11

To verify the consistency of the matrices used as example in this chapter (in particular of matrix in 3.4), the following steps must be made:

- calculation of vector **y** multiplying the matrix by its priority vector $\mathbf{x}_{C1.2}$ in (3.25), as in (3.66):

$$\mathbf{y} = [\mathbf{A}] \cdot \mathbf{x}_{C1.2} = \begin{bmatrix} 1 & 6 & 2 \\ 1/6 & 1 & 1/4 \\ 1/2 & 4 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.588 \\ 0.089 \\ 0.323 \end{bmatrix} = \begin{bmatrix} 1.768 \\ 0.268 \\ 0.973 \end{bmatrix} \tag{3.66}$$

- calculation of vector **z**, as in (3.67):

$$\mathbf{z} = \begin{bmatrix} \frac{y_1}{x_1} \\ \frac{y_2}{x_2} \\ \frac{y_3}{x_3} \end{bmatrix} = \begin{bmatrix} 3.009 \\ 3.009 \\ 3.009 \end{bmatrix} \tag{3.67}$$

- determination of the rank of the matrix, n:

$$n = 3 \tag{3.68}$$

- estimation of λ_{max} using vector **z**:

$$\widetilde{\lambda}_{max} = \frac{(z_1 + z_2 + z_3)}{3} = \frac{(3.009 + 3.009 + 3.009)}{3} = 3.009 \tag{3.69}$$

- calculation of Consistency Index, CI:

$$CI \simeq \frac{\widetilde{\lambda}_{max} - n}{n - 1} = \frac{3.009 - 3}{3 - 1} = 0.005 \tag{3.70}$$

- calculation of Consistency Ratio, CR:

$$CR = \frac{CI}{RI_n} = \frac{CI}{RI_3} = \frac{0.005}{0.52} = 0.003 \tag{3.71}$$

  that results less than 0.10 so that the matrix considered can be used as consistent.

BOX 12

If matrix $[\mathbf{A}^*_{C1.2}]$ in (3.59) is evaluated about its consistency it results the following computations:

- calculation of $\mathbf{x}^*$:

$$\mathbf{x}^* = \begin{bmatrix} 0.205 \\ 0.078 \\ 0.717 \end{bmatrix} \tag{3.72}$$

- calculation of $\mathbf{y}^*$:

$$\mathbf{y}^* = [\mathbf{A}^*_{C1.2}] \cdot \mathbf{x}^* = \begin{bmatrix} 1 & 6 & 1/8 \\ 1/6 & 1 & 1/4 \\ 8 & 4 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.205 \\ 0.078 \\ 0.717 \end{bmatrix} = \begin{bmatrix} 0.764 \\ 0.292 \\ 2.670 \end{bmatrix} \tag{3.73}$$

- calculation of $\mathbf{z}^*$:

$$\mathbf{z}^* = \begin{bmatrix} \frac{y_1}{x_1} \\ \frac{y_2}{x_2} \\ \frac{y_3}{x_3} \end{bmatrix} = \begin{bmatrix} 3.726 \\ 3.726 \\ 3.726 \end{bmatrix} \tag{3.74}$$

- determination of the rank of the matrix, n^*:

$$n^* = 3 \tag{3.75}$$

- estimation of λ^*_{max}:

$$\widetilde{\lambda}^*_{max} = \frac{(z^*_1 + z^*_2 + z^*_3)}{3} = \frac{(3.726 + 3.726 + 3.726)}{3} = 3.726 \tag{3.76}$$

- calculation of CI^*:

$$CI^* \simeq \frac{\widetilde{\lambda}^*_{max} - n^*}{n^* - 1} = \frac{3.726 - 3}{3 - 1} = 0.363 \tag{3.77}$$

- calculation of CR^*:

$$CR^* = \frac{CI^*}{RI_n} = \frac{CI^*}{RI_3} = \frac{0.363}{0.52} = 0.250 \tag{3.78}$$

  so that $CR^*$is greater than 0.10 and the matrix $[\mathbf{A}^*_{C1.2}]$ can not be considered reliable and used for the decision.

Table 3.3: An example of rank reversal

	Candidate 1 voters	**Candidate 2 voters**	**Candidate 3 voters**	**Winner**
Scenario A	45%	**55%**	–	Candidate 2
Scenario B	**45%**	40%	15%	Candidate 1

A first problem of AHP is related to the procedure itself, that is very long, especially when a great number of alternatives or criteria are possible.

Another aspect for which AHP can be criticized is the high level of subjectivity (see section 3.3.5).

About the mathematical procedure there is an issue with the normalization. A normalization like the one described in section 3.3.2 does not take into account the real distance among the indicators before the normalization. This fact could bring to a unreliable (or wrong) solution. For example: a problem is defined by two indicators and two alternatives; alternative 1 is a little better than alternative 2 in indicator A, but have the indicator B very worse than alternative 2. If the two indicators have the same importance, a normalization without tricks could not recognize the best solution and could bring to a tie, whereas if the decision-maker looks at the indicators before the normalization alternative 2 could be chosen (a little worsening in indicator A means an important improvement in indicator B).

The last important problem of AHP analysis is the most critical and is the so-called *rank reversal* [62]: in certain condition (especially as the number alternatives increases [72]) the addition or the removal of an alternative could bring to a rank reversal among two or more of the other alternatives. This phenomenon can appear also when the added (or removed) solution should not influence the rank of the other ones, for example because it is the worst of all or it is similar or equal to another one [73].

A clear and classic example of the phenomenon rank reversal is an election: in scenario A there are only two candidates and it will win the most voted; in scenario B there are the same two candidates and a third one, weaker than the others. If this third candidate is voted mainly, or only, by voters who supported the winner in scenario A, it is possible that the winner in scenario A does not win in scenario B. The example is summarized in table 3.3 (Candidate 1, who loses in scenario A, wins in scenario B, even though without the absolute majority of the votes).

So it is important to avoid, when possible, a condition that can bring to a rank reversal. In any case, as previously explained, it is necessary a wide analysis of results in order to validate them and to understand if they can be considered reliable for a decision or not.

Against these limits, AHP model has some important strengths, underlined before in the chapter, that make the process reliable and suitable for a decision in some contexts.

A recall of the main strengths is the following:

- The result of AHP method is a vector that represents the level of preference to attribute to each alternative. So it is possible to establish a ranking of the different alternatives in addition to determine the best one.

- As already said, a hierarchical analysis method carries out a cost-benefit analysis in non-monetary terms, so that it is possible to use qualitative as well as quantitative indicators. This makes not necessary to know the exact values of the indicators but only to estimate them, even qualitatively.

- The construction of a hierarchy makes possible to break down any kind of problem, even a very complex one, in simpler elements. This make the definition of the set of indicators easier.
- The ease of the comparison made with the pairwise comparison instead of a comparison among all the element together makes the procedure user-friendly.

Chapter 4

Definition and implementation of the model for gas flaring reduction problems

4.1 Weaknesses of AHP related to the specific problem of gas flaring reduction

Referring to the AHP in the specific problem of gas flaring reduction, its weaknesses could be neglected with some consideration that should not affect importantly the results and the final decision.

First of all, considering the nature of the problem (i.e. gas flaring reduction with international companies, governments and international agencies involved) the length of the procedure for the pairwise comparison is not very relevant: probably a discussion between the stakeholders about, for example, what alternative must be included in the analysis or what environmental or social impact of the project must be acceptable is more time-expensive than the compilation of the matrices.

Secondly, if subjectivity can generally be a problem in a decision method, it could have a minor impact in a flaring problem because of the possible great number of stakeholders (the differences of interests should be compensated each other) and because of the desirable reliability of the stakeholders in their judgments.

Thirdly, the problem with the normalization of quantitative indicators has been solved in this application of AHP by modifying the range of the normalization in relation to the maximum real difference in values of absolute indicators: the maximum range for the normalization is chosen between 1 and 9 making a qualitative comparison (using the Saaty's scale) between the maximum and the minimum value of each indicator.

For example, considering the *water consumption* indicator in a context where the availability of water is not a critical factor: if alternatives show the maximum value of the indicator *water consumption* equal to $120l/s$ and the minimum value equal to $100l/s$ it is clear that the difference is not excessively wide, but it can be considered *moderately important or plus*, i.e. a value of 4 can be selected as the maximum value for normalization, according to Saaty's scale (table 3.1). So the value of this indicator will be normalized to 4 in the alternative with a consumption equal to $120l/s$, to 1 in the alternative with a consumption equal to $100l/s$ and other intermediate values, which refer to the remaining alternatives, will be normalized proportionally in a range between 1 and 4.

Considering rank reversal, it should not be likely to have alternatives very similar to each other because different configurations of the same plant should be optimized in the feasibility study.

Therefore, in this context rank reversal should only be possible between alternatives with close global priorities, but a little difference in the global priorities should not be considered as decisive because of the uncertainty of the measurements (or of the estimations) of qualitative indicators and the subjectivity of qualitative indicators values and comparisons.

Finally, if two or more alternatives get a result very close to each other, it will be good to consider all candidates tied for the solution of the problem, and eventually re-apply the model considering only these alternatives if they occupy the top positions in the obtained ranking.

In conclusion AHP can be considered as a good method to be used to evaluate gas flaring reduction problems and to make a decision, with strengths and weaknesses that can be monitored.

Once decided to use the Analytical Hierarchy Process method, it is necessary to define precisely the hierarchy of the problem that must solve (i.e. in this case the problem is to make a choice between various alternatives to reduce or eliminate gas flaring in existing plants or to avoid this practice in green-field plants).

According to the method, at the top-level of the hierarchy there is the goal of the problem. As a logical consequence of the concepts explained in paragraph 1.1.2, the three dimensions of sustainability (Economic, Environmental, Social) coincide with three fundamental criteria (Economic criterion, Environmental criterion, Social criterion), which form the second level of the hierarchy, in order to be sure to evaluate all the aspects of sustainability and the main aspects relating to each dimension.

Each of these fundamental criteria is then evaluated on the basis of several specific sub-criteria, which together form a third level of the hierarchy.

The choice of the sub-criteria is based on guidance provided by IAEA and United Nations regarding the themes which make up the three dimensions of sustainability [74, 75], without forgetting the specific issues of the analyzed problem.

It is important to underline that it is assumed eligible alternatives have already been selected by the involved company (or companies) on the basis of a criterion of technical feasibility.

In addition to the technical constraint there could be some further constraints due to the necessity of the stakeholder (government, investors, companies, ...), e.g. a minimum increase in the local level of occupation requested by the government, or a minimum economic return for the investors, etc. These constraints are a second screening among the alternatives to be evaluated.

Therefore, the aim is to select the alternative that gives the best compromise between the three dimensions that make up sustainability, assuming that the alternatives that are not feasible from a technical point of view have already been rejected.

Selected sub-criteria for each main criterion are listed below:

- **Economic sub-criterion** Economic viability, sustainability and performance (with particular reference to the involved companies or the investors).

- **Environmental sub-criteria** Land use; freshwater use; impact on atmosphere; noise level; short and long-term impact on the concerned territory.

- **Social sub-criteria** Direct and indirect employment; energy access (electricity, heat and fuels access); health.

It is necessary to identify a number of indicators in order to give an estimation of the performance of each considered alternative with respect to each criterion and sub-criterion in the form of quantitative data or, when this is not possible, in the form of qualitative judgments, as seen in paragraph 3.3.2.

Hence, it is possible to define a set of indicators that allow a comparison among different alternatives and consequently the definition of a ranking, obtained applying the AHP, that constitutes a valid support to make a final decision.

Hence, the selection of indicators is based on three main criteria:

1. They should be characterized by a high degree of relevance respect to the criterion to which they refer, since non-relevant indicators would cause a distorted decision when applying AHP or, at least, make the decision more difficult.

2. Each indicator should provide critical information not available from other indicators.

3. Collecting data to calculate each indicator should be most likely achievable in a pre-feasibility project phase. As a matter of facts, typically the choice among the possible alternatives takes place during the early stages of the project. For this reason indicators that require very specific and detailed information are not realistically eligible. In any case, not to exclude aspects that are difficult to evaluate from a numerical point of view, alongside quantitative indicators qualitative indicators are proposed, too. Quantitative indicators assume values that are directly collected from the pre-feasibility study or are calculated on the basis of other available data. Qualitative indicators, at the contrary, are based on a reasoned evaluation performed by decision-makers.

These criteria are the same used by the Commission on Sustainable Development to select core indicators of countries sustainable development [75]:

> Core indicators fulfill three criteria. First, they cover issues that are relevant for sustainable development in most countries. Second, they provide critical information not available from other indicators. Third, they can be calculated by most countries with data that is either readily available or could be made available within reasonable time and costs. Conversely, indicators that are not part of the core are either relevant only for a smaller set of countries, provide complementary information to core indicators or are not easily available for most countries.

The identified indicators, that for the Environmental and Social dimensions are similar or coincide with those pointed out by IAEA in [74] but also in projects about CDM or other themes of sustainable development such as in [76], are presented and discussed in the next paragraphs, grouped according to their respective dimensions.

Table 4.1 gives an overview of the indicators set.

4.2 Economic dimension indicators

The selected economic indicators are three: Internal Rate of Return (IRR), Pay-Back Time (PBT) and Net Present Value (NPV). These three indicators were chosen because

Table 4.1: Indicators for each dimension

Dimension	**Indicators**
Economic	Internal Rate of Return, Pay-Back Time, Net Present Value
Environmental	Soil consumption, H_2O consumption, Air pollution, Noise, Impact during construction, Impact on biodiversity
Social	Number of local employees, Electrical connections increase, Heat connections increase, Local distribution of fuel, Impact on health, Other local impacts

at least one of them is almost always used directly by a company or an investor to evaluate the various alternatives and is therefore available without requiring further calculations[1]. Clearly they provide an indication in accordance with the sub-criterion of the economic dimension earlier introduced (*economic viability, sustainability and performance*).

In particular, generally investors tend to use only IRR, assuming that it gives sufficient information to make a choice among alternatives. However in some specific situations, some of which are described below for each indicator, also PBT and/or NPV are evaluated. Therefore the decision-makers can decide the activation of one or more of the three selected indicators depending on the specific context.

Internal Rate of Return and Net Present Value (quantitative) All other things being equal, using internal rate of return and net present value measurements to evaluate alternatives often results in the same findings.

However, there are a number of situations for which using IRR as an economic indicator is not as effective as using NPV.

IRR major limitation is also its greatest strength: it uses one single discount rate to evaluate each investment. In most cases, when it is supposable that IRR and NPV leads to the same results, IRR is preferred to NPV because it simplifies projects to a single number that the decision-maker can use to determine the best project in terms of profitability. At the contrary, the evaluation of NPV is inherently complex and requires assumptions at each stage (discount rate, likelihood of receiving the cash payment, etc) but gives better results with long-term projects that have multiple cash flows at different discount rates, or in case of very uncertain cash flows. Moreover, IRR could be not adequate to make a comparison among projects characterized by a very different amount of the investment because it does not take directly into account and does not give explicit information about the size of the investment [77, 78].

PBT (quantitative) Payback-time refers to the length of time within which the benefits received from an investment can repay the costs incurred during the time in question while ignoring the remaining time periods in the planning horizon.

PBT ignores any benefits that occur after the payback period and, therefore, does not measure profitability, but provide useful information in the case of projects in geographical areas characterized by high risks due to social or political instability: in this case alternatives with shorter PBT could be preferred to other alternatives even if their IRR or NPV evaluation indicates lower financial returns.

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[1] Unlike the other dimensions, in this case it is not possible to use economic indicators suggested by IAEA since they do not refer to the specific context of industrial installations (and therefore do not provide necessary information).

4.3 Environmental dimension indicators

Indicators in the Environmental dimension should provide an evaluation of the main potential impacts and hazards associated to the construction of each considered alternative in a gas flaring reduction project.

The consultation of some international standards, in particular [79] and [80], together with the analysis described in paragraph 1.1.2, helped to identify the main sources of environmental impact to be taken into account by indicators and, consequently, the their selection.

Many environmental indicators are available from IAEA [74], however, as already mentioned above, some of them requires very specific data, which are not easily available in an initial pre-feasibility study[2]. That is why in some cases qualitative indicators where selected instead of more complex (and quantitative) ones suggested by the IAEA.

Soil Consumption (quantitative) Soil consumption gives a quantitative evaluation for the sub-criterion *land use*. In fact, it is the physical area occupied by a project, i.e. the area occupied by pipeline networks, process units, utilities, buildings and new roads or railways.

In general, an estimation of the area is given by (4.1):

$$A = w \cdot l \tag{4.1}$$

where A is the computed area. In the case of pipeline networks w is evaluated as the width of the pipeline permanent right-of-way area and l is the length of the pipeline. In the case of roads or railways, at the contrary, w is the permanently modified stripe's width and l is the length of the new road or railway.

Finally, the area occupied by process units, utilities or buildings includes also parking areas, safety areas between the buildings, internal roads, flaring zones, ...

Water consumption (quantitative) This is the indicator for the *fresh water use* sub-criterion, and is defined as the total quantity of water that is not returned in the same, or quite the same, conditions in which it was taken. For example the quantity of water consumed by evaporating towers or converted in chemical processes and the consumption of potable water.

Air pollution (quantitative) Air pollution refers to the sub-criterion *impact on atmosphere* and is obtained from the aggregation of three sub-indicators: $CO_{2equivalent}$, SOx and NOx.

$\mathbf{CO_{2equivalent}}$ (quantitative) This second-level indicator permits the evaluation of the effects deriving from CO_2 and pollutant emissions in terms of their Global Warming Potential. It is evaluated as follows:

$$CO_{2equivalent} = CO_{2emissions} + \sum_i k(i) \cdot p(i) \tag{4.2}$$

where $p(i)$ is the i-th considered pollutant emissions and $k(i)$ is the corresponding coefficient of conversion[3].

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[2] For example, it is clear that a quantitative evaluation of the particulate matter released to the stacks or of a change in the level of water quality is not realistic, at least in this planning stage.

[3] IPCC provides a coefficient of conversion for the most common greenhouse substances [1].

SOx(quantitative) Emissions of SO_x deriving from the process.

NOx(quantitative) Emissions of NO_x deriving from the process.

Noise (qualitative) This indicator obviously refers to the *noise level* sub-criterion and is the result of a qualitative estimation of the noise level causing a deterioration of the environmental conditions, with particular reference to the living conditions of local population. The indicator values should be estimated taking into account the increase in noise levels, compared to the previous situation, due to new plants operations considering also the distance among the plant and residential areas.

Impact during construction (qualitative) This is a qualitative estimation of the temporary impact due to the construction phase. The indicator provides an evaluation for the sub-criterion *short-term impact on the concerned territory.* The estimation should take into account the amount of soil that is temporary occupied by the construction site and is then reinstated, the temporary local resources usage and the inconvenience caused to the population. The estimation should particularly take into account the temporary aspect of the construction, meaning a low weight in the hierarchy (paragraph 3.3.3). Since it is possible to clear up the area affected by the construction of the temporary facilities at the end of works, the weight of this indicator should be small, since it evaluates a short-term effect, unlike other indicators.

Impact on ecosystem (qualitative) The indicator is the result of a qualitative estimation of the impact of the project on the local ecosystem giving an evaluation for the sub-criterion *long-term impact on the concerned territory.* The impact increases with the importance of the ecosystems affected by the project, and assumes very high values in case of crossing sensible areas. Everything else being equal, the impact should be in general proportional to the affected area size.

In case an Environmental Impact Assessment (EIA) was performed for each of the alternatives[4], information deriving from the document can be used as a basis to assign values to this indicator.

4.4 Social dimension indicators

This group of six indicators gives information about the impact of the considered alternatives on the local population in relation to the improvement of the energy access conditions, the consequences on health and eventually the direct and indirect improvement of employment. Once again, an adaptation to the specific context was obtained starting from indicators proposed by IAEA [74], in order to assess as much as possible the various social issues related to a gas flaring reduction project while allowing a simple evaluation of indicators.

Number of employees (quantitative) This is the indicator for the direct employment criterion, and it is evaluated as the number of people recruited from local communities that are directly employed in the plant. If this information is not available, an estimation can be made on the basis of a comparison with other similar existing facilities.

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[4] EIA is mandatory to obtain final authorizations to build a plant, but generally the realization of this kind of study is unlikely in a pre-feasibility stage.

Other local impacts (qualitative) This indicator is used in the case of an evident improvement in indirect employment induced by the presence of the new plants (e.g. the creation of cooperatives for the distribution of liquid fuels produced in the plants). Clearly in this case a quantitative estimation of the number of people involved is very critical, that is why the indicator is evaluated in a qualitative manner.

Electrical connections increase (quantitative) *Electrical connections increase* permits an evaluation of the aspects of a project related to the sub-criterion *electrical energy access*. The indicator is defined as the estimated number of new electrical connections to houses (i.e. the number of families that gets new access to electricity or that records a significant improvement in the quality of the electric service in those cases where interruptions in supply occur frequently).

A simple estimation of the indicator is given by the (4.3):

$$Electrical\,Connections\,Increase = P_{tot}/P \tag{4.3}$$

where P is the power consumption for the average living unit connected and P_{tot} is the power of the new electrical plant fed by recovered associated gas.

Of course, if it is not planned to build a power plant in any of the considered alternatives, this indicator should not be considered.

Heat connections increase (quantitative) The indicator is defined as the estimated number of living units getting a new connection to a district heating network. It refers to the sub-criterion *thermal energy access*.

A simple estimation of the indicator is given by the (4.4):

$$Heat\,Connections\,Increase = Q_{tot}/Q \tag{4.4}$$

where Q is the average heat power required from each living unit, which depends on climatic conditions and on the level of building isolation, and Q_{tot} is the heat power available at the thermal central station discounted of the thermal network losses.

If district heating replaces other heating systems, the three air pollution second-level indicators (CO_{2equi}, SO_x, NO_x) should take into account not only the additional emissions due to heat production[5] but also the reduction of emissions due to the replacement of the previous heating systems. Moreover, decision-makers should take into account the related positive impact on health for the alternative considered when assigning a value to the impact on the indicator *impact on health* (as will be explained later).

The same considerations made for electrical connections increase indicator apply in the case that none of the alternatives considers the presence of a district heating plant.

Local distribution of fuel (quantitative) The indicator, that refers to the sub-criterion *fuels energy access,* is obtained from the aggregation of three sub-indicators: *natural gas connections increase*, *local GTL/LPG users increase* and *local LNG users increase*. The indicator should be used only if at least one of the three second-level indicators is active, i.e. if at least one of the considered alternatives contemplates a distribution of natural gas, synthetic fuels, LPG or LNG to local populations.

If these fuels are used in substitution of other fuels (e.g. LPG instead of wood for cooking purposes) air pollution indicators and impact on health indicator should consider not only new emissions but also the reduction of emissions due to abandonment of previous

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[5] Additional emissions should not be considered if heat power is recovered from process utilities.

systems (the concept is similar to that observed in the discussion of heat connections increase indicator).

NG connections increase (quantitative) Number of new local users connected to natural gas distribution network.

Local GTL/LPG users increase (quantitative) Number of new local users of synthetic fuels deriving from associated gas conversion and/or number of new local users of LPG deriving from associated gas fractionation.

Local LNG users increase (quantitative) Number of new local users of LNG obtained from associated gas recovering and treating.

Impact on health (qualitative) This qualitative indicator permits the evaluation of the impact on local populations health conditions due to each of the alternatives, in accordance with the requirements of the sub-criterion *health*. Decision-makers should consider the following main factors to estimate impact magnitude: distance between settlements and plants, kind and entity of emissions, eventual increase of traffic.

4.5 Implementation of the AHP model with selected indicators

4.5.1 Hierarchy and matrices set up

After the selection of the indicators, the following step is the implementation of the model based on the AHP.

First of all, it is necessary to set up the final breaking down of the general problem "choosing the best alternative for reducing gas flaring" in hierarchical levels. The chosen levels of hierarchy were explained at the beginning of this chapter.

Figure 4.1 shows the complete hierarchy: at the top of the hierarchy the goal, i.e. a reduction of gas flaring.

Main criteria to select the best alternative coincide with the three dimensions of sustainability, and each of these main criteria is the result of aggregation of several criteria relating to a third level of the hierarchy. Each of these criteria is evaluated in a quantitative or qualitative manner thanks to selected indicators.

Secondly, as it was explained in section 3.3, the method entails the implementation of a set of pairwise comparison matrices that must be filled in each time according to the alternatives under analysis and of the step-by-step procedure to obtain the aggregation of the various levels of the hierarchy, from the bottom to the top. Hence, empty matrices for each level and aggregation algorithm referred to the goal of reducing gas flaring are introduced in next paragraphs.

Lowest level of the hierarchy In this level there are two matrices allowing pairwise comparisons among sub-indicators within the indicators to which they relate[6]. Alongside each matrix there is the normalized main eigenvector $\mathbf{x}$, whose components are the weight

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[6] Therefore, in these matrices pairwise comparisons of indicators are obtained by estimating the importance of each other by assigning a numerical value based on Saaty's scale.

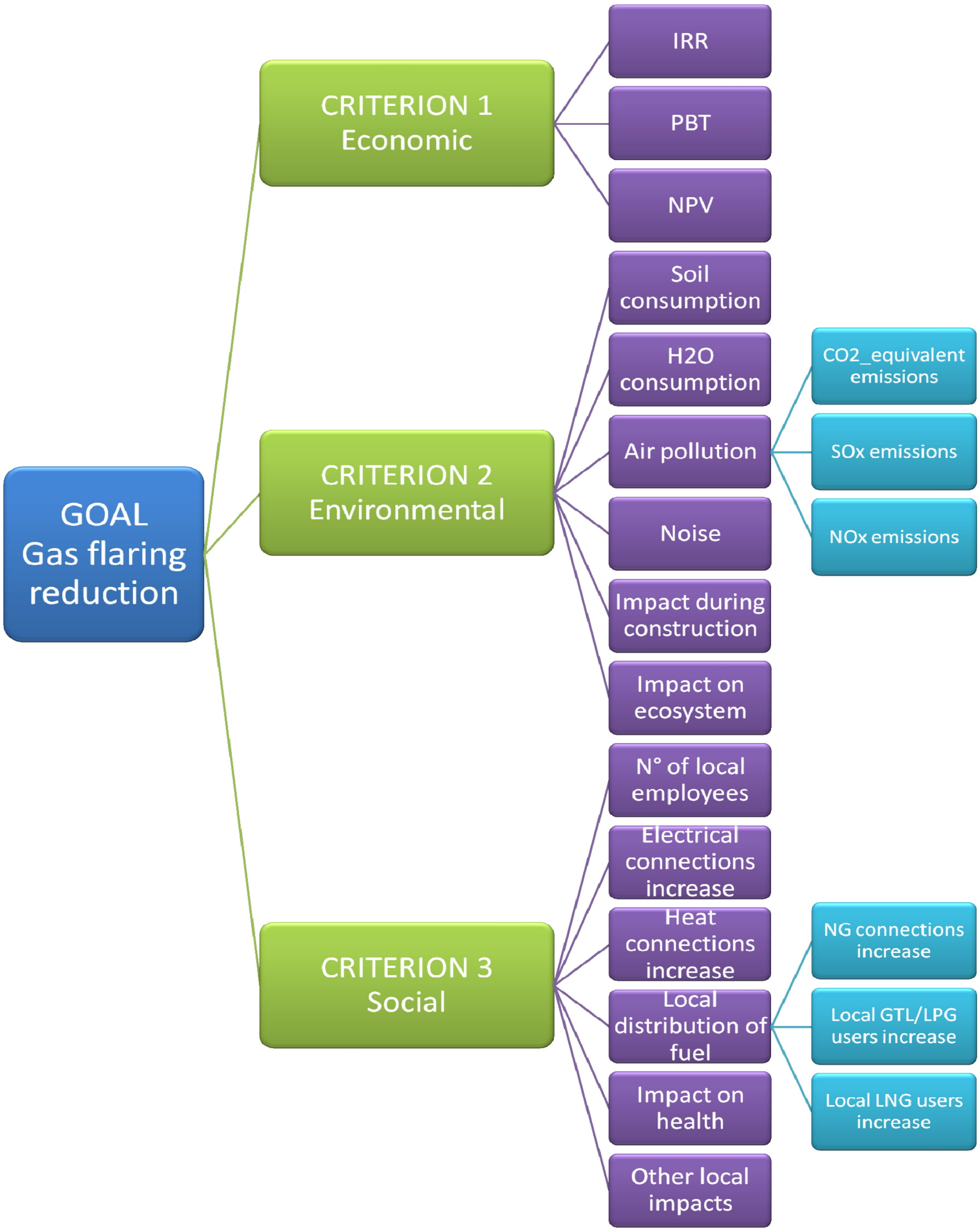


Figure 4.1: Scheme of the hierarchy

assigned to each sub-indicator. For this reason it is also called *priority vector,* as already said in the previous chapter.

Air pollution	1) CO_{2equi}	2) SO_x	3) NO_x	$\mathbf{x_a}$
1) CO_{2equi}	1 vs 1	1 vs 2	1 vs 3	x_{a1}
2) SO_x	2 vs 1	2 vs 2	2 vs 3	x_{a2}
3) NO_x	3 vs 1	3 vs 2	3 vs 3	x_{a3}

Local distribution of fuel	1)	2)	3)	$\mathbf{x_l}$
1) NG connections increase	1 vs 1	1 vs 2	1 vs 3	x_{l1}
2) Local GTL/LPG connections inc.	2 vs 1	2 vs 2	2 vs 3	x_{l2}
3) Local LNG users increase	3 vs 1	3 vs 2	3 vs 3	x_{l3}

In the same level there are six matrices allowing pairwise comparisons among alternatives within each sub-indicator[7]. This time, alongside each matrix there is a normalized main eigenvector whose components are the weight assigned to each alternative. The matrices for the sub-indicators of the indicator *Air pollution* are the following:

$\mathbf{CO_{2equi}}$	A1	A2	...	An	$\mathbf{x}_{CO_2}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	$x_{CO_2 1}$
A2	A2 vs A1	A2 vs A2	...	A2 vs An	$x_{CO_2 2}$
...	$\vdots$	$\vdots$	Ai vs Aj	$\vdots$	...
An	An vs A1	An vs A2	...	An vs An	$x_{CO_2 n}$

$\mathbf{SO}_x$	A1	A2	...	An	$\mathbf{x}_{SO_x}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	$x_{SO_x 1}$
A2	A2 vs A1	A2 vs A2	...	A2 vs An	$x_{SO_x 2}$
...	$\vdots$	$\vdots$	Ai vs Aj	$\vdots$	...
An	An vs A1	An vs A2	...	An vs An	$x_{SO_x n}$

$\mathbf{NO}_x$	A1	A2	...	An	$\mathbf{x}_{NO_x}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	$x_{NO_x 1}$
A2	A2 vs A1	A2 vs A2	...	A2 vs An	$x_{NO_x 2}$
...	$\vdots$	$\vdots$	Ai vs Aj	$\vdots$	...
An	An vs A1	An vs A2	...	An vs An	$x_{NO_x n}$

Priority vectors of each alternative compared with respect to each sub-criterion of *Air pollution*, placed side by side, make up the partial performance matrix $[\mathbf{W}_{Air}]$:

$$[\mathbf{W}_{Air}] = \left[\ \mathbf{x}_{CO_2} \mid \mathbf{x}_{SO_x} \mid \mathbf{x}_{NO_x}\ \right] = \begin{bmatrix} x_{CO_2 1} & x_{SO_x 1} & x_{NO_x 1} \\ x_{CO_2 2} & x_{SO_x 2} & x_{NO_x 2} \\ \cdots & \cdots & \cdots \\ x_{CO_2 n} & x_{SO_x n} & x_{NO_x n} \end{bmatrix} \tag{4.5}$$

Priority vector $\mathbf{x}_{AirPoll}$ within the indicators *Air pollution* is obtained multiplying $[\mathbf{W}_{Air}]$ by vector $\mathbf{x}_a$:

$$\mathbf{x}_{AirPoll} = [\mathbf{W}_{Air}] \cdot \mathbf{x}_a \tag{4.6}$$

---

[7] Therefore, in these matrices pairwise comparisons of alternatives are obtained by estimating the performance of each other by assigning a numerical value based on Saaty's scale or by an automatic filling in, starting from available data, in the case of quantitative indicators.

Instead, the matrices for the sub-indicators referring to the indicator *Local distribution of fuel* are the following:

$$\begin{array}{ccccc|c}
\textbf{NG} & \text{A1} & \text{A2} & \dots & \text{An} & \mathbf{x}_{NG} \\
\text{A1} & \text{A1 vs A1} & \text{A1 vs A2} & \dots & \text{A1 vs An} & x_{NG1} \\
\text{A2} & \text{A2 vs A1} & \text{A2 vs A2} & \dots & \text{A2 vs An} & x_{NG2} \\
\text{...} & \vdots & \vdots & \text{Ai vs Aj} & \vdots & \dots \\
\text{An} & \text{An vs A1} & \text{An vs A2} & \dots & \text{An vs An} & x_{NGn}
\end{array}$$

$$\begin{array}{ccccc|c}
\textbf{GTL/LPG} & \text{A1} & \text{A2} & \dots & \text{An} & \mathbf{x}_{GTL/LPG} \\
\text{A1} & \text{A1 vs A1} & \text{A1 vs A2} & \dots & \text{A1 vs An} & x_{GTL/LPG1} \\
\text{A2} & \text{A2 vs A1} & \text{A2 vs A2} & \dots & \text{A2 vs An} & x_{GTL/LPG2} \\
\text{...} & \vdots & \vdots & \text{Ai vs Aj} & \vdots & \dots \\
\text{An} & \text{An vs A1} & \text{An vs A2} & \dots & \text{An vs An} & x_{GTL/LPGn}
\end{array}$$

$$\begin{array}{ccccc|c}
\textbf{LNG} & \text{A1} & \text{A2} & \dots & \text{An} & \mathbf{x}_{LNG} \\
\text{A1} & \text{A1 vs A1} & \text{A1 vs A2} & \dots & \text{A1 vs An} & x_{LNG1} \\
\text{A2} & \text{A2 vs A1} & \text{A2 vs A2} & \dots & \text{A2 vs An} & x_{LNG2} \\
\text{...} & \vdots & \vdots & \text{Ai vs Aj} & \vdots & \dots \\
\text{An} & \text{An vs A1} & \text{An vs A2} & \dots & \text{An vs An} & x_{LNGn}
\end{array}$$

Therefore:

$$[\mathbf{W}_{LocalDistFuel}] = \left[\begin{array}{c|c|c} \mathbf{x}_{NG} & \mathbf{x}_{GTL/LPG} & \mathbf{x}_{LNG} \end{array}\right] \tag{4.7}$$

and

$$\mathbf{x}_{Fuel} = [\mathbf{W}_{LocalDistFuel}] \cdot \mathbf{x}_{l} \tag{4.8}$$

Third level of hierarchy The logic with which required matrices for this level are identified is the same used in the precedent level.

Hence, in this case matrices allowing pairwise comparisons among indicators are three, one for each main criterion (i.e. one for each dimension of sustainability).

Also in this case, alongside each matrix there is the normalized main eigenvector **x**, whose components are the weight assigned to each indicator (hereafter the terms *criterion* and *indicator* will be used indifferently when referring to the same element of the hierarchy).

The matrices related to the Economic, Environmental and Social criteria are the subsequent:

$$\begin{array}{rccc|c}
\textbf{Economic} & 1) & 2) & 3) & \mathbf{x}_{Eco} \\
1)\ IRR & 1 \text{ vs } 1 & 1 \text{ vs } 2 & 1 \text{ vs } 3 & x_{Eco1} \\
2)\ PBT & 2 \text{ vs } 1 & 2 \text{ vs } 2 & 2 \text{ vs } 3 & x_{Eco2} \\
3)\ NPV & 3 \text{ vs } 1 & 3 \text{ vs } 2 & 3 \text{ vs } 3 & x_{Eco3}
\end{array}$$

$$\begin{array}{rcccccc|c}
\textbf{Environmental} & 1) & 2) & 3) & 4) & 5) & 6) & \mathbf{x}_{Env} \\
\text{1) Soil cons.} & 1 \text{ vs } 1 & 1 \text{ vs } 2 & \dots & \dots & 1 \text{ vs } 5 & 1 \text{ vs } 6 & x_{Env1} \\
\text{2) } H_2O \text{ cons.} & 2 \text{ vs } 1 & 2 \text{ vs } 2 & \dots & \dots & 2 \text{ vs } 5 & 2 \text{ vs } 6 & x_{Env2} \\
\text{3) Air pollution} & 3 \text{ vs } 1 & 3 \text{ vs } 2 & \dots & \dots & 3 \text{ vs } 5 & 3 \text{ vs } 6 & x_{Env3} \\
\text{4) Noise} & 4 \text{ vs } 1 & 4 \text{ vs } 2 & \dots & \dots & 4 \text{ vs } 5 & 4 \text{ vs } 6 & x_{Env4} \\
\text{5) Imp. during cons.} & 5 \text{ vs } 1 & 5 \text{ vs } 2 & \dots & \dots & 5 \text{ vs } 5 & 5 \text{ vs } 6 & x_{Env5} \\
\text{6) Imp. on ecosystem} & 6 \text{ vs } 1 & 6 \text{ vs } 2 & \dots & \dots & 6 \text{ vs } 5 & 6 \text{ vs } 6 & x_{Env6}
\end{array}$$

Social	1)	2)	3)	4)	5)	6)	$\mathbf{x}_{Soc}$
1) N° of local empl.	1 vs 1	1 vs 2	...	...	1 vs 5	1 vs 6	x_{Soc1}
2) El. conn. inc.	2 vs 1	2 vs 2	...	...	2 vs 5	2 vs 6	x_{Soc2}
3) Heat conn. inc.	3 vs 1	3 vs 2	...	...	3 vs 5	3 vs 6	x_{Soc3}
4) Distr. of local fuel	4 vs 1	4 vs 2	...	...	4 vs 5	4 vs 6	x_{Soc4}
5) Impact on healt	5 vs 1	5 vs 2	...	...	5 vs 5	5 vs 6	x_{Soc5}
6) Other local imp.	6 vs 1	6 vs 2	...	...	6 vs 5	6 vs 6	x_{Soc6}

The matrices allowing pairwise comparisons among alternatives within each sub-indicator are 13: one for each indicator excluding *Air pollution* and *Distribution of local fuel*, because they are the result of the aggregation of sub-indicators, as it was shown in the previous paragraph.

In particular, referring to the Economic criterion:

IRR	A1	A2	...	An	$\mathbf{x}_{IRR}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	x_{IRR1}
A2	A2 vs A1	A2 vs A2	...	A2 vs An	x_{IRR2}
...	⋮	⋮	Ai vs Aj	⋮	...
An	An vs A1	An vs A2	...	An vs An	x_{IRRn}

PBT	A1	A2	...	An	$\mathbf{x}_{PBT}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	x_{PBT1}
A2	A2 vs A1	A2 vs A2	...	A2 vs An	x_{PBT2}
...	⋮	⋮	Ai vs Aj	⋮	...
An	An vs A1	An vs A2	...	An vs An	x_{PBTn}

NPV	A1	A2	...	An	$\mathbf{x}_{NPV}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	x_{NPV1}
A2	A2 vs A1	A2 vs A2	...	A2 vs An	x_{NPV2}
...	⋮	⋮	Ai vs Aj	⋮	...
An	An vs A1	An vs A2	...	An vs An	x_{NPVn}

Vector $\mathbf{x}_{Economic}$ of weights for each alternative within the Economic criterion is obtained multiplying $[\mathbf{W}_{Eco}]$ by vector $\mathbf{x}_{Eco}$:

$$\mathbf{x}_{Economic} = [\mathbf{W}_{Eco}] \cdot \mathbf{x}_{Eco} \tag{4.9}$$

where

$$[\mathbf{W}_{Eco}] = \left[\begin{array}{c|c|c} \mathbf{x}_{IRR} & \mathbf{x}_{PBT} & \mathbf{x}_{NPV} \end{array} \right] \tag{4.10}$$

Referring to the Environmental and Social criterion obviously the matrices are similar. For example, the matrix referring to *Soil consumption* is:

Soil consumption	A1	A2	...	An	$\mathbf{x}_{Soil}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	x_{Soil1}
A2	A2 vs A1	A2 vs A2	...	A2 vs An	x_{Soil2}
...	⋮	⋮	Ai vs Aj	⋮	...
An	An vs A1	An vs A2	...	An vs An	x_{Soiln}

And the matrix referring to *Number of local employees* is:

N of local emp.	A1	A2	...	An	$\mathbf{x}_{Empl}$
A1	A1 vs A1	A1 vs A2	...	A1 vs An	x_{Empl1}
A2	A2 vs A1	A2 vs A2	...	A2 vs An	x_{Empl2}
...	⋮	⋮	Ai vs Aj	⋮	...
An	An vs A1	An vs A2	...	An vs An	x_{Empln}

Therefore:

$$[\mathbf{W}_{Env}] = \left[\ \mathbf{x}_{Soil}\ \middle|\ \mathbf{x}_{Water}\ \middle|\ \mathbf{x}_{AirPoll}\ \middle|\ \mathbf{x}_{Noise}\ \middle|\ \mathbf{x}_{Const}\ \middle|\ \mathbf{x}_{Ecosys}\ \right] \tag{4.11}$$

$$[\mathbf{W}_{Soc}] = \left[\ \mathbf{x}_{Empl}\ \middle|\ \mathbf{x}_{El}\ \middle|\ \mathbf{x}_{Heat}\ \middle|\ \mathbf{x}_{Fuel}\ \middle|\ \mathbf{x}_{Health}\ \middle|\ \mathbf{x}_{Other}\ \right] \tag{4.12}$$

and

$$\mathbf{x}_{Environmental} = [\mathbf{W}_{Env}] \cdot \mathbf{x}_{Env} \tag{4.13}$$

$$\mathbf{x}_{Social} = [\mathbf{W}_{Soc}] \cdot \mathbf{x}_{Soc} \tag{4.14}$$

Second level of hierarchy Only one matrix is necessary in this level, whose function is to assign a weight to each of the three main criteria:

Goal	1)	2)	3)	$\mathbf{x}_g$
1) Economic	1 vs 1	1 vs 2	1 vs 3	x_{g1}
2) Environmental	2 vs 1	2 vs 2	2 vs 3	x_{g2}
3) Social	3 vs 1	3 vs 2	3 vs 3	x_{g3}

First level of hierarchy: ranking of alternatives to reach the goal The final ranking of alternatives is reached by applying the (4.15):

$$\mathbf{x}_{Goal} = [\mathbf{W}_{Goal}] \cdot \mathbf{x}_g \tag{4.15}$$

where

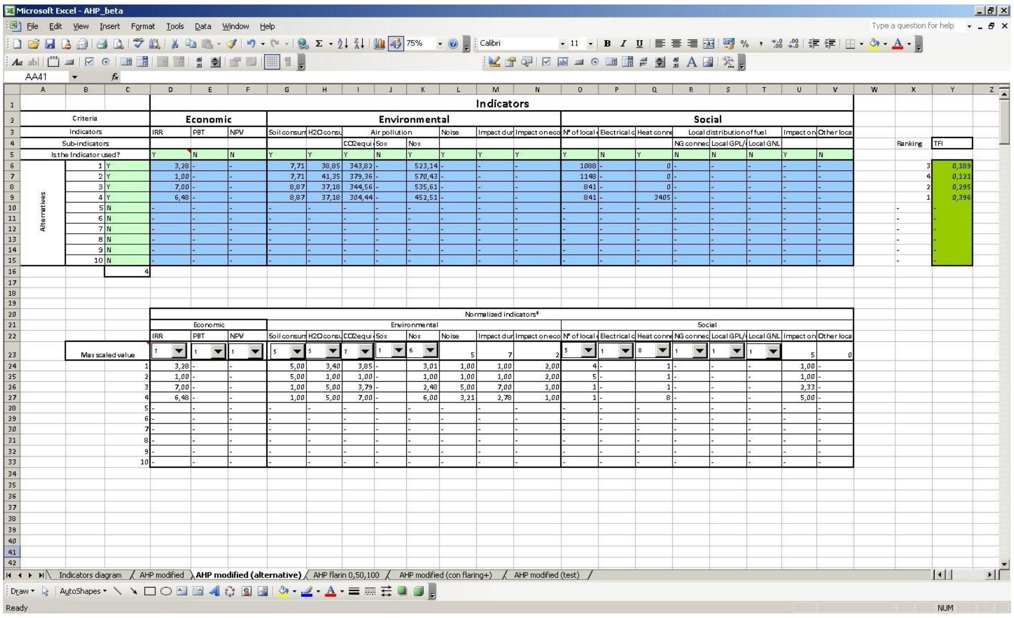
$$[\mathbf{W}_{Goal}] = \left[\ \mathbf{x}_{Economic}\ \middle|\ \mathbf{x}_{Environmental}\ \middle|\ \mathbf{x}_{Social}\ \right] \tag{4.16}$$

4.5.2 Software implementation and verification: *Excel* model and *Super Decision*

Software implementation Although there are several commercial software suitable to perform the modeling of a decision problem using the method AHP, an AHP Microsoft *Excel*-based model was developed in order to better understand the model itself, the compilation procedure and the logic behind it.

A screen-shot of the model is given in figure 4.2. In particular, in the upper right it is shown the final result (in the group of cells on a green background).

In the *Excel* model up to 10 alternatives can be compared (all together or some of them separately). Indicators can be activated or not depending on the problem and the analyzed scenario.



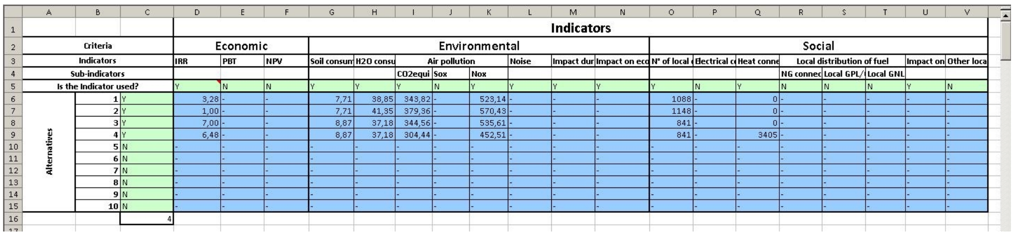
Indicators

Criteria			Economic			Environmental								Social									
Indicators			IRR	PBT	NPV	Soil consum	H2O consu	Air pollution			Noise	Impact dur	Impact on eco	N° of local	Electrical c	Heat conne	Local distribution of fuel			Impact on	Other loca		
Sub-indicators								CO2equi	Sox	Nox							NG connec	Local GPL/	Local GNL			Ranking	TFI
Is the Indicator used?			Y	N	N	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	N	N	N	Y	N		
Alternatives	1	Y	3,28	-	-	7,71	38,85	343,82	-	523,14	-	-	-	1088	-	0	-	-	-	-	-	3	0,189
	2	Y	1,00	-	-	7,71	41,35	379,36	-	570,43	-	-	-	1148	-	0	-	-	-	-	-	4	0,121
	3	Y	7,00	-	-	8,87	37,18	344,56	-	535,61	-	-	-	841	-	0	-	-	-	-	-	2	0,295
	4	Y	6,48	-	-	8,87	37,18	304,44	-	452,51	-	-	-	841	-	3405	-	-	-	-	-	1	0,396
	5	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	7	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	8	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	9	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		4																					

Normalized indicators*

		Economic			Environmental								Social							
		IRR	PBT	NPV	Soil consum	H2O consu	CO2equi	Sox	Nox	Noise	Impact dur	Impact on eco	N° of local	Electrical c	Heat conne	NG connec	Local GPL/	Local GNL	Impact on	Other loca
Max scaled value		7	1	1	5	5	7	1	6	5	7	2	5	1	8	1	1	1	5	0
	1	3,28	-	-	5,00	3,40	3,85	-	3,01	1,00	1,00	2,00	4	-	1	-	-	-	1,00	-
	2	1,00	-	-	5,00	1,00	1,00	-	1,00	1,00	1,00	2,00	5	-	1	-	-	-	1,00	-
	3	7,00	-	-	1,00	5,00	3,79	-	2,48	5,00	7,00	1,00	1	-	1	-	-	-	2,33	-
	4	6,48	-	-	1,00	5,00	7,00	-	6,00	3,21	2,78	1,00	1	-	8	-	-	-	5,00	-
	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

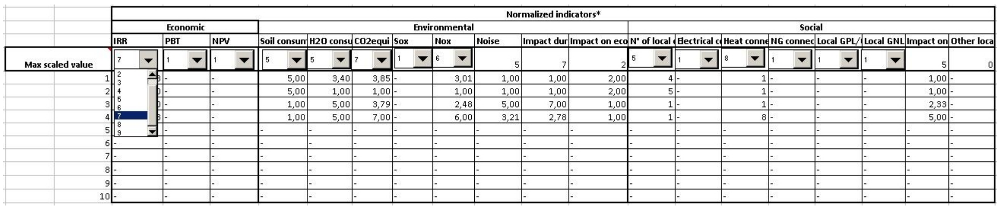
Figure 4.2: Main windows screen-shot



Indicators

Criteria			Economic			Environmental								Social							
Indicators			IRR	PBT	NPV	Soil consum	H2O consu	Air pollution			Noise	Impact dur	Impact on eco	N° of local	Electrical c	Heat conne	Local distribution of fuel			Impact on	Other loca
Sub-indicators								CO2equi	Sox	Nox							NG connec	Local GPL/	Local GNL		
Is the Indicator used?			Y	N	N	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	N	N	N	Y	N
Alternatives	1	Y	3,28	-	-	7,71	38,85	343,82	-	523,14	-	-	-	1088	-	0	-	-	-	-	-
	2	Y	1,00	-	-	7,71	41,35	379,36	-	570,43	-	-	-	1148	-	0	-	-	-	-	-
	3	Y	7,00	-	-	8,87	37,18	344,56	-	535,61	-	-	-	841	-	0	-	-	-	-	-
	4	Y	6,48	-	-	8,87	37,18	304,44	-	452,51	-	-	-	841	-	3405	-	-	-	-	-
	5	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	7	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	8	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	9	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		4																			

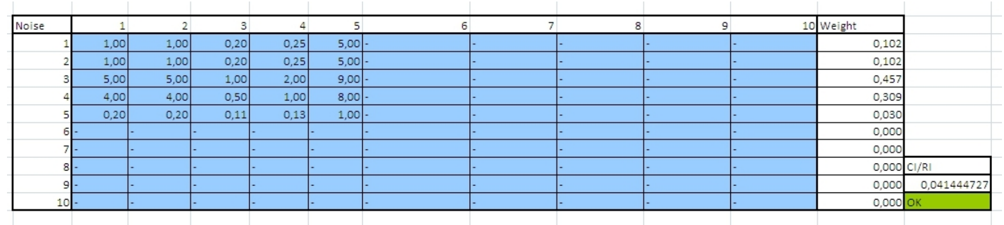
Figure 4.3: Quantitative data table



Normalized indicators*

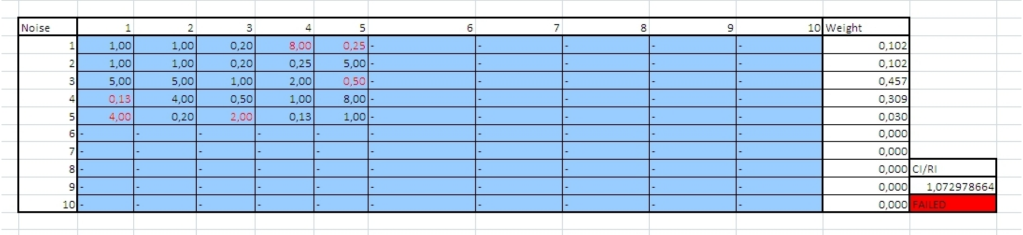
		Economic			Environmental								Social							
		IRR	PBT	NPV	Soil consum	H2O consu	CO2equi	Sox	Nox	Noise	Impact dur	Impact on eco	N° of local	Electrical c	Heat conne	NG connec	Local GPL/	Local GNL	Impact on	Other loca
Max scaled value		7	1	1	5	5	7	1	6	5	7	2	5	1	8	1	1	1	5	0
	1	[illegible]	-	-	5,00	3,40	3,85	-	3,01	1,00	1,00	2,00	4	-	1	-	-	-	1,00	-
	2	[illegible]	-	-	5,00	1,00	1,00	-	1,00	1,00	1,00	2,00	5	-	1	-	-	-	1,00	-
	3	[illegible]	-	-	1,00	5,00	3,79	-	2,48	5,00	7,00	1,00	1	-	1	-	-	-	2,33	-
	4	[illegible]	-	-	1,00	5,00	7,00	-	6,00	3,21	2,78	1,00	1	-	8	-	-	-	5,00	-
	5	[illegible]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 4.4: Quantitative normalized data table



Noise	1	2	3	4	5	6	7	8	9	10	Weight	
1	1,00	1,00	0,20	0,25	5,00	-	-	-	-	-	0,102	
2	1,00	1,00	0,20	0,25	5,00	-	-	-	-	-	0,102	
3	5,00	5,00	1,00	2,00	9,00	-	-	-	-	-	0,457	
4	4,00	4,00	0,50	1,00	8,00	-	-	-	-	-	0,309	
5	0,20	0,20	0,11	0,13	1,00	-	-	-	-	-	0,030	
6	-	-	-	-	-	-	-	-	-	-	0,000	
7	-	-	-	-	-	-	-	-	-	-	0,000	
8	-	-	-	-	-	-	-	-	-	-	0,000	CI/RI
9	-	-	-	-	-	-	-	-	-	-	0,000	0,041444727
10	-	-	-	-	-	-	-	-	-	-	0,000	OK

(a) Matrix correctly filled in



Noise	1	2	3	4	5	6	7	8	9	10	Weight	
1	1,00	1,00	0,20	8,00	0,25	-	-	-	-	-	0,102	
2	1,00	1,00	0,20	0,25	5,00	-	-	-	-	-	0,102	
3	5,00	5,00	1,00	2,00	0,50	-	-	-	-	-	0,457	
4	0,13	4,00	0,50	1,00	8,00	-	-	-	-	-	0,309	
5	4,00	0,20	2,00	0,13	1,00	-	-	-	-	-	0,030	
6	-	-	-	-	-	-	-	-	-	-	0,000	
7	-	-	-	-	-	-	-	-	-	-	0,000	
8	-	-	-	-	-	-	-	-	-	-	0,000	CI/RI
9	-	-	-	-	-	-	-	-	-	-	0,000	1,072978664
10	-	-	-	-	-	-	-	-	-	-	0,000	FAILED

(b) Matrix not consistent

Figure 4.5: *Noise* matrix

With regard to the quantitative indicators, starting from data inserted by the users in a table (figure 4.3), normalized values are automatically obtained once the user selected the maximum value from a drop-down menu (figure 4.4) and pairwise matrices are automatically filled in.

At the contrary, pairwise matrices referring to qualitative indicators are directly filled in by users.

A consistency test for each matrix allows to verify the comparisons. To give an example, in figure 4.5a five alternatives are active and the *Noise* matrix was filled in correctly, as shown by the value of $CR = {}^{CI}/_{RI} < 0.10$ (paragraph 3.3.4) and the "OK" on a green background in the cell at the bottom right. At the contrary, figure 4.5b shows the same matrix with some values changed so that the test fails because of the value of $CR > 0.10$, and therefore in the control cell appears the message "FAILED" on a red background.

Vectors of the weights are obtained using the geometric mean approximated method (see section 3.3).

In the model it is possible to change the weights of each indicator monitoring the change in the solution both numerically and graphically in order to understand the influence of the assigned weights to the partial and final results.

Software verification To validate the developed model, all matrices were filled in with two series of random values and four alternatives were activated.

Obtained results were compared with those obtained using the same numbers and alternatives in the software *Super Decision*[8].

This software is developed by *Creative Decisions Foundation*, a foundation established personally by Thomas Saaty. A screen-shot of the main window of the software set for the resolution of a gas flaring reduction problem is shown in figure 4.6.

The results of the comparison, that are shown in table 4.2, prove a good level of agreement between the *Excel* model and *Super Decision*. The light differences in results

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[8] `http://www.superdecisions.com`

Table 4.2: Comparison between results obtained with the *Excel* model and *Super Decision*

Serie	**Alternative**	***Excel***	***Super Decisions***	**Deviation** [%]
1	1	0.2613	0.2593	0.77
	2	0.2396	0.2434	1.56
	3	0.2403	0.2416	0.54
	4	0.2588	0.2557	1.21
2	1	0.1811	0.1822	0.60
	2	0.2027	0.2006	1.05
	3	0.3949	0.3954	0.13
	4	0.2218	0.2218	0.23

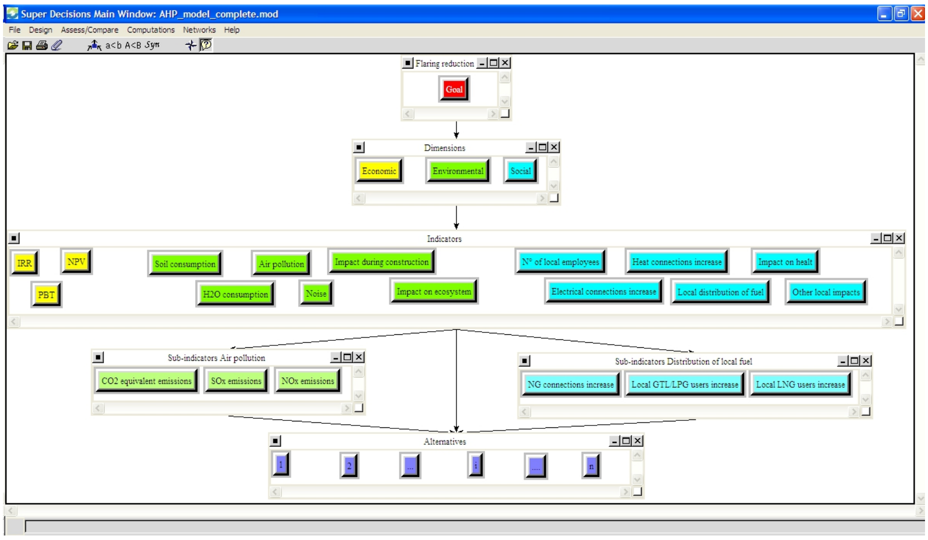

Figure 4.6: Hierarchy in Super Decision Software for a gas flaring reduction problem

should be mainly attributed to a different method of eigenvectors extraction.

Super Decision was also used to do the sensitivity analysis, as explained in chapter 5, because of the complexity of implementation of the necessary code in *Microsoft Excel.*

Part III

Application and results

Chapter 5

Russia: a case study

The application of the model presented in the previous chapters to a real case was possible thanks to a collaboration with *Techint E&C S.p.a.*

A stage conducted in the company allowed collecting and processing real data from a feasibility study for a project aimed at the recovery of associated gas from Western Siberia commissioned by a major petrochemical Russian company.

About 40% of Russia's recoverable oil reserves are located in fields where there is a more or less significant amount of associated gas.

The issue of associated gas utilization has long been discussed at the Russian government level, and sporadic attempts to solve it were already made in the past. However, a much stronger focus of the Russian Government on the issue has been observed starting from 2007. In April 2007, President Vladimir Putin paid a special attention to the problem in his Presidential Address to the Russian Federal Assembly [81] noting that

> The Russian oilfields currently flare more than 20 billion cubic meters per year of associated gas at the lowest estimate. Such wastefulness is unacceptable. Especially given that a system of measures with proven efficiency is known and applied globally for a long time. We should establish an appropriate accounting system, increase environmental penalties and tighten license requirements for subsurface users without further delay.

Afterwards President Putin asked to take measures in order to bring the level of associated gas utilization to the average global level of 95% by 2011. In response to this request several action plan drafts regarding the issue of associated gas utilization were gradually released. Nonetheless, in December 2008 the Ministry of Natural Resources and Ministry of Energy suggested postponing introduction of a mandatory standard for oil companies to utilize 95% of produced associated gas from 2011 to 2014 [82].

In other words, de facto most of the Russian associated gas at the moment is still flared at wellhead. Quantities are enormous: as it was shown in 1.1.1, a NOAA estimation revealed that about 35 billions cubic meters were flared in 2010. To give a more concrete idea of the amount of gas involved, this corresponds to about 45% of the gas consumed in 2009 in Italy[1].

Most of Russia's gas flaring takes place in the Khanty Mansiysk, Yamalo-Nenetsk and northern Tomskaya regions of Western Siberia, within a $650000km^2$ region (that is a region larger than France). The region lies within $500km$ of the Urengoy and Yamburg

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[1] `http://dgerm.sviluppoeconomico.gov.it/dgerm/consumi/gas/Consumi_gas_2009.xls`

(a) Urengoi (b) Luginetsk

Figure 5.1: Gas flaring in western Siberia (source: Science Photo Library)

gas fields, which are the main suppliers of the gas pipelines serving European Russia, Western Europe, and the countries in between (figures 5.1 show flaring areas respectively in proximity of Urengoy and Luginetsk fields). The area is almost totally uninhabited, is covered with mixed forest composed of aspens, birch trees, fir trees and pines and is characterized by extreme conditions: in winter the temperature can drop to $-60^{\circ}C$ and the ground is completely frozen, while in summer moderate temperatures are reached, and the area becomes a huge swamp dotted with ponds and lakes. The road network is almost nonexistent, and often impassable because of ice or summer flooding [47].

Figure 5.2 shows a satellite map of the region where the presence of flaring areas is denoted in red.

Techint's project refers to an area situated in northern Tomskaya region (the area is emphasized on the map in figure 5.2) that is spread over about $40000km^2$. Here average annual temperature is $-1.2^{\circ}C$, average temperature in January totals $-20.4^{\circ}C$ and in July $+17.4^{\circ}C$. Absolute maximum temperature is $36^{\circ}C$, absolute minimum is $-53^{\circ}C$ (2010 regional statistics).

All-season roads are not available due to a high degree formations of peat: in winter transport via roads is available from mid-December to the end of March, meanwhile cargo delivery is feasible in spring, during the high-water period of about 3 weeks in May-June.

This fact causes serious consequences such as an increase in difficulties associated with cost estimation and makes a careful definition of the construction phase absolutely necessary.

The project involves over 30 fields in Novosibirsk area, with a total flow rate of raw gas from fields of more than 2500 million standard cubic meters per year[2]. Appendix B gives information about these fields. At the moment most of associated gas from these fields is flared.

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[2] Average data based on the assumption of a project working life of 15 years. It is expected that the production peak exceeds 3000 millions of Smc per year.

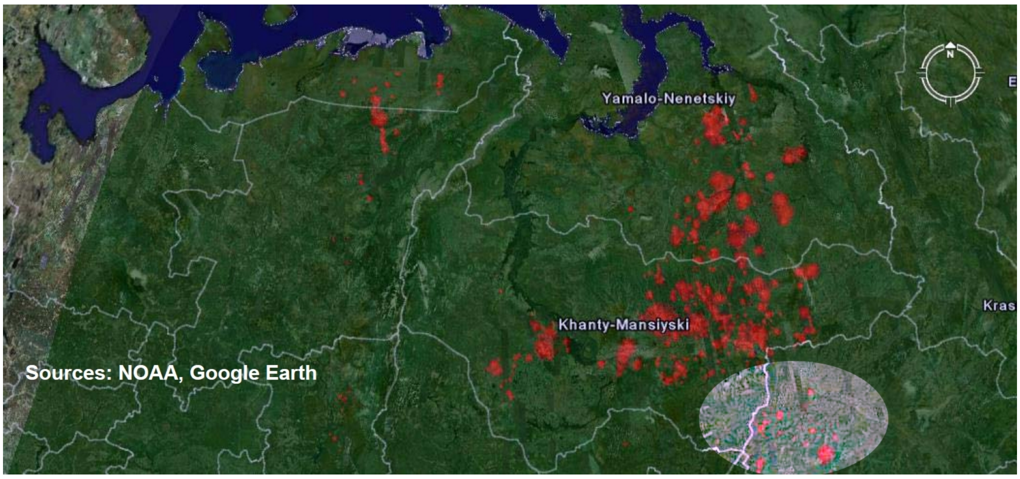

Figure 5.2: Satellite map of Western Siberia flaring areas (source: NOAA; Google Earth)

Table 5.1: Average composition of collected gas

	Composition [%]
CH_4	82.19
C_2H_6	5.82
C_3H_8	4.80
iC_4H_{10}	1.20
nC_4H_{10}	1.92
C_{5+}	1.58
N_2	1.25
CO_2	1.22

The average composition of the collected gas is shown in table 5.1.

5.1 Definition and selection of alternatives

The definition of the alternatives is the result of a complex screening based on several considerations and steps: first of all, a preliminary study of various technologies[3] based on the criterion of technical feasibility and a market analysis led to choose as the ultimate goal the sale of natural gas and of heavier components separately. Therefore, this choice implies the collection of the raw gas and the construction of a treatment and conditioning plant.

Because of the prohibitive environmental conditions in the region of the fields, the absence of other plants for support and the absence of any communication route, raw gas must be collected using a gathering network of pipelines, compressed and delivered through a main pipeline to a less isolated place, where the separation of natural gas from heavier fractions can take place. An analysis of the area allowed to identify two possible locations of the gas processing plant, that hereafter will be called *site B* and *site T*.

The main challenges related with the evaluation of the pipeline networks were:

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[3] All the technologies examined in chapter 2, with the exception of GTL, were considered in this first step.

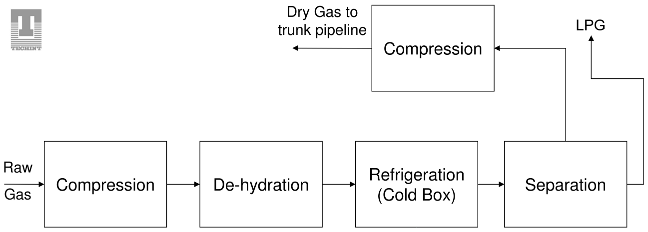

Figure 5.3: Treatment and conditioning plant block scheme (source: *Techint*)

- large number of fields involved and vastness of the region, which makes possible hundreds of different possible configuration of the pipeline networks;
- presence of components which could condense as a liquid phase along the lines (both water and hydrocarbons);
- long distances to be covered (hundreds of kilometers) in a generally cold climate and on a terrain which is mostly swampy and badly accessible during a large time of the year;
- existence of two different points of arrival for the main delivering pipeline.

The definition of the network of gathering pipelines is approximately independent from the final destination of the raw gas[4], and was obtained by *Techint* by developing a calculation model that allows the minimization of the distances to be covered (and of CAPEX, as a consequence) taking also into account the different requirements of the owners of the fields. Over 100 configurations were tested before getting the final configuration.

To avoid problems due to condensation occurrence or formation of hydrates during the transportation, it was decided that a first raw gas dehydration should be performed at fields[5], and it was planned to lay the main pipeline underground, despite the fact that the swampy nature of the soil makes the operation very complex.

The fact that a more or less detailed level of separation of the gas can be performed, coupled with the presence of two possible locations of the treatment and conditioning plant led finally *Techint* and the client of the project to select four alternatives. In each alternative gas flaring is completely eliminated, and flare stacks are preserved only for safety or emergency requirements.

All the alternatives, therefore, on the one hand consider the sale of dry gas and its introduction into existing natural gas pipelines, and on the other hand contemplate the sale of heavier fractions which are used directly on site or are sent to remote markets by railway.

Before the introduction, dry gas is compressed by means of a centrifugal compressor driven by a gas turbine equipped with low NO_x combustion control.

A block scheme of the treatment and conditioning plant is shown in figure 5.3.

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[4] At the contrary, the definition of the main raw gas pipeline path obviously depends on the location of the treatment plant.

[5] This first process of dehydration is performed through glycol absorption. Because of the cold temperatures reached during conditioning process, a more effective dehydration is required. In this case solid desiccant dehydrators are adopted.

Figure 5.4: Satellite map of Site B (source: Google Earth)

Figure 5.5: Satellite map of trans-Siberian railway in Site B (source: Google Earth)

5.2 Description of selected alternatives

Site B alternatives The first two alternatives consider the possibility of building a pipeline that transports gas from the fields to Site B covering a distance of about $600km$. Located in the Novosibirsk region, Site B stands astride the trans-Siberian railway (figures 5.4 and 5.5).

These two alternatives, denominated *Site B1* (*B1*) and *Site B2* (*B2*), provide for the building of a plant for separating the heavier components from natural gas in an area adjacent to the city. While natural gas is introduced into a gas dorsal pipeline present in the proximity, heavier liquid hydrocarbons are loaded onto waggons and delivered to markets via the trans-Siberian railway.

The two alternatives B1 and B2 differ depending on the level of separation of heavy fractions: the alternative B1 considers only the possibility of obtaining natural gas and a mixture of heavier components (C_{3+}). The alternative B2 instead provides for a more stringent separation, obtaining natural gas (C_1 and C_2), propane (C_3), iso and normal butane (C_4) and C_{5+} as separate products. In both cases all the products are exported and sold on non-local markets.

Figure 5.6: Satellite map of Site T (source: Google Earth)

Since Site B is currently not provided of an infrastructure system capable of handling the quantities of products expected, these alternatives require the construction of auxiliary structures like a railway connection, loading racks and connection roads.

Site T alternatives Alternatives three (*T1*) and four (*T2*) evaluate the chance of building a pipeline in order to transfer the gas near the city of Site T, situated in the homonym region (figure 5.6) and south-east of the gas fields area. In this case the distance between the fields and the city is about $800km$. Site T population overtakes half a million of inhabitants and a wide industrial area is located north of the city.

T1 contemplates the construction of a conditioning unit to separate propane and heavier components (C_{3+}) from natural gas in this area. Natural gas is than introduced in an existent secondary branch of a pipeline which leads into a main gas pipeline located a few tens of kilometres away. A near existent petrochemical plant makes use of the heavier fractions as feed to obtain poly-olefins.

T2 is similar to T1, but it also contemplates the recovery of the residual heat in the combusted gases from turbines used to drive compressors. Heat is used to feed an existent district heating network that permits the substitution of old gas boilers in a Site T quarter.

5.3 Data selection and evaluation of indicators

In order to obtain an assessment of the alternatives considered by the model previously described, it is necessary to decide which indicators among those selected in the model assume effectively relevance in the context of this project, and therefore should be activated.

In a second step it is necessary to select the data with which it is possible to estimate or calculate each activated quantitative indicator. Depending on the differences that occur among the values of each indicator in the various alternatives it is also necessary to select a maximum value to obtain normalized values (section 4.5).

Finally, the process requires to build the matrix of active qualitative indicators.

Deactivation of indicators not relevant in the specific West Siberian project context Regarding the Economic dimension, data provided directly by *Techint* were used. Data derive directly from the results of the feasibility study conducted by the company for the alternatives listed above.

Since the size of the investment does not vary considerably between the different alternatives, IRR was selected as main economical parameter because it provides a simple and immediate comparison of the alternatives. An estimation of CAPEX for each alternative was performed in order to evaluate IRR. At the contrary, NPV and PBT have not been calculated nor considered. For this reason, IRR is the only economic indicator activated.

In the Environmental dimension only the SO_x indicator is disabled. This choice is based on the assumption, proven by data on the composition of the gas from the fields, of an irrelevant presence (or of the absence) of sulfur compounds in the gas as a result of treatment processes performed in the proximity of the wells.

Finally, among the Social dimension indicators, the following ones are disabled:

- *Electrical connections increase*: as a matter of fact, none of the considered alternatives contemplate the distribution of electricity outside the plants: electricity is produced with the only purpose of satisfying the internal need of the utilities.
- *Local distribution of fuel*s, because there is no distribution of gaseous or liquid fuels to the local population.

Figure 5.7 shows the general indicators scheme with deactivated indicators in red and crossed out.

Evaluation of indicators Quantitative indicators assume numerical values directly provided from *Techint*'s pre-feasibility study or derived from a reprocessing of data from the same study. In particular, environmental indicators values were obtained thanks to an estimation performed using procedures described in 4.3. Appendix C shows further information and data for each alternative.

Table 5.2 shows the value assigned to each indicator for each alternative. Table 5.3 shows values normalized on the basis of Saaty's scale and the maximum (Max) value used to obtain normalization. Each of the Max values was assigned on the basis of considerations analogous to those made in section 4.5.

Formulas (5.1) and (5.2) show how the normalization is obtained respectively in the case where a high value of the indicator implies a benefit or a cost:

$$1 + \frac{i_j - \min(I)}{\max(I) - \min(I)} \cdot (Max - 1) \tag{5.1}$$

$$1 + \frac{\max(I) - i_j}{\max(I) - \min(I)} \cdot (Max - 1) \tag{5.2}$$

where i_j is the value that indicator i assumes within alternative j, I is the set of values of the indicator i and Max is the maximum value selected by user.

Pairwise alternatives comparisons matrices for each quantitative indicator can be automatically filled starting from normalized values. Consequently, a normalized priority vector for each indicator is obtained. To give an example, table 5.4a reports IRR matrix filled in with ratios between normalized indicators and table 5.4b reports the final matrix with the normalized priority vector $\mathbf{x}_{IRR}$.

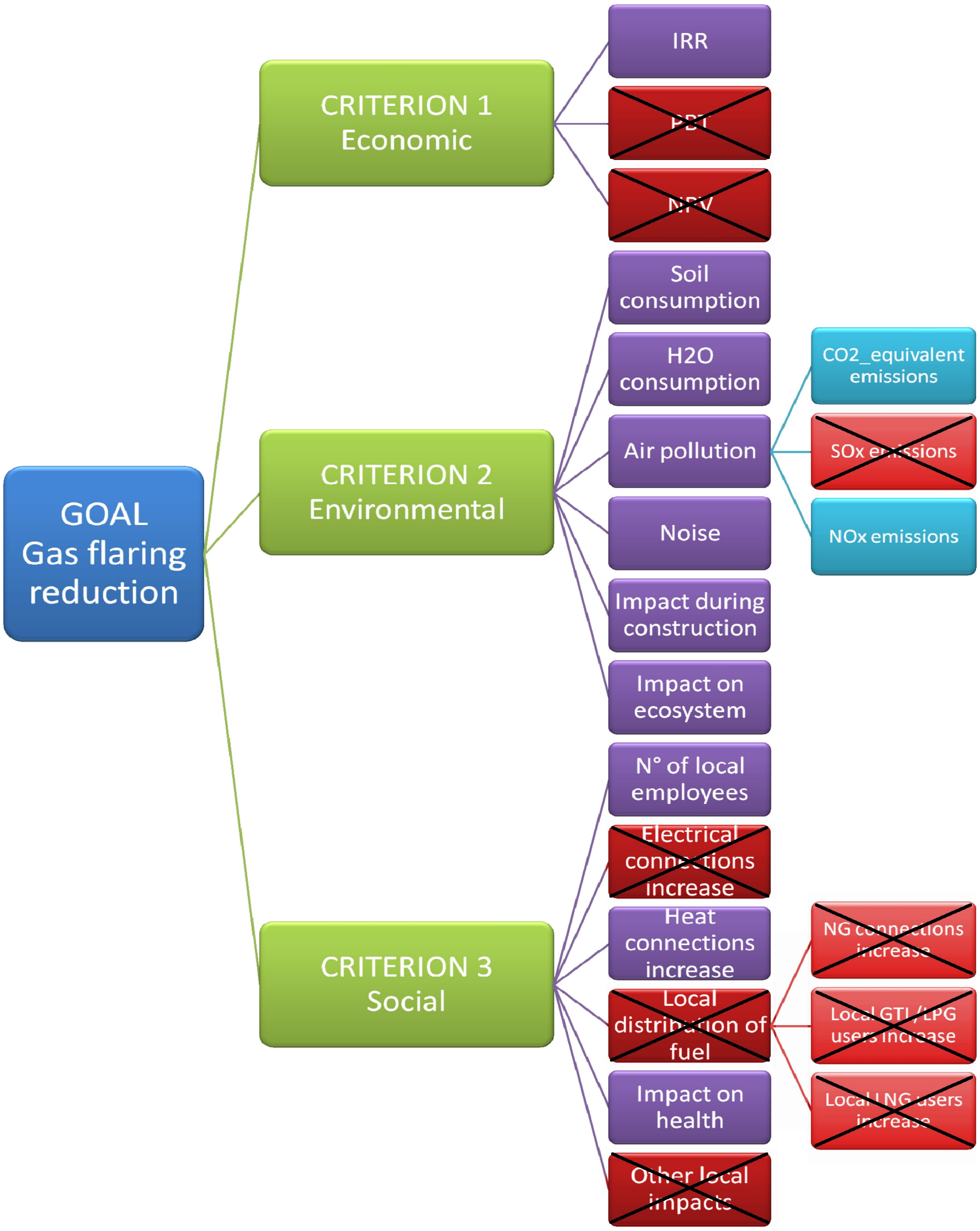

Figure 5.7: Scheme with deactivated indicators

Table 5.2: Values assigned to each indicator

	B1	**B2**	**T1**	**T2**	
IRR*	3.28	1.00	7.00	6.48	–
Soil consumption	7.71	7.71	8.87	8.87	km^2
H_2O consumption	38.85	41.35	37.18	37.18	m^3/h
CO_{2equi}	343.82	379.36	344.56	301.44	$MM\ Sm^3/y$
NOx	523.14	570.43	535.61	462.51	ton/y
N° of local employees	1088	1148	841	841	–
Heat connections increase	0	0	0	3405	–

* Only normalized values of IRR can be quoted because of confidentiality reasons

Table 5.3: Normalized values assigned to each indicator

	B1	**B2**	**T1**	**T2**	*Max*
IRR	3.28	1.00	7.00	6.48	*7*
Soil consumption	5	5	1	1	*5*
H_2O consumption	3.40	1	5	5	*5*
CO_{2equi}	3.85	1	3.79	7	*7*
NOx	3.01	1.00	2.48	6	*6*
N° of local employees	4	5	1	1	*5*
Heat connections increase	1	1	1	8	*8*

Table 5.4: IRR matrix and priority vector

(a) IRR matrix: calculation

IRR	B1	B2	T1	T2
B1	$^{3.28}/_{3.28}$	$^{3.28}/_{1}$	$^{3.28}/_{7}$	$^{3.28}/_{6.48}$
B2	$^{1}/_{3.28}$	$^{1}/_{1}$	$^{1}/_{7}$	$^{1}/_{6.48}$
T1	$^{7}/_{3.28}$	$^{7}/_{1}$	$^{7}/_{7}$	$^{7}/_{6.48}$
T2	$^{6.48}/_{3.28}$	$^{6.48}/_{1}$	$^{6.48}/_{7}$	$^{6.48}/_{6.48}$

(b) IRR matrix: final result and vector $\mathbf{x}$

IRR	B1	B2	T1	T2	$\mathbf{x}_{IRR}$
B1	1.00	3.28	0.47	0.51	0.184
B2	0.31	1.00	0.14	0.15	0.056
T1	2.14	7.00	1.00	1.08	0.394
T2	1.98	6.48	0.93	1.00	0.365

At the contrary, qualitative indicators obviously cannot be quantified starting from numerical data. For this reason a relative priority is assigned to each couple of alternatives directly in each pairwise matrix.

In next sections a filled pairwise comparison matrix for each quantitative and qualitative indicator is given. In the case of qualitative indicators matrices are given together with the considerations made in order to assign submitted values[6]. Used degrees of comparison refer to Saaty's definitions (table 3.1).

Matrices are introduced starting from the lowest level of hierarchy, following the main branches of the scheme in figure 5.7.

5.3.1 Economic dimension

IRR

	B1	B2	T1	T2	x_{IRR}
B1	1.00	3.28	0.47	0.51	0.184
B2	0.31	1.00	0.14	0.15	0.056
T1	2.14	7.00	1.00	1.08	0.394
T2	1.98	6.48	0.93	1.00	0.365

5.3.2 Environmental dimension

CO$_{2\text{equivalent}}$ emissions

	B1	B2	T1	T2	x_{CO_2}
B1	1.00	3.85	1.02	0.55	0.246
B2	0.26	1.00	0.26	0.14	0.064
T1	0.98	3.79	1.00	0.54	0.242
T2	1.82	7.00	1.85	1.00	0.448

NO$_x$emissions

	B1	B2	T1	T2	x_{NO_x}
B1	1.00	3.01	1.21	0.50	0.241
B2	0.33	1.00	0.40	0.17	0.080
T1	0.82	2.48	1.00	0.41	0.198
T2	2.00	6.00	2.42	1.00	0.481

Soil consumption

	B1	B2	T1	T2	x_{Soil}
B1	1.00	1.00	5.00	5.00	0.417
B2	1.00	1.00	5.00	5.00	0.417
T1	0.20	0.20	1.00	1.00	0.083
T2	0.20	0.20	1.00	1.00	0.083

---

[6] As usual, higher values correspond to positively better performances.

Water consumption

	B1	B2	T1	T2	x_{Water}
B1	1.00	3.40	0.68	0.68	0.236
B2	0.29	1.00	0.20	0.20	0.069
T1	1.47	5.00	1.00	1.00	0.347
T2	1.47	5.00	1.00	1.00	0.347

Noise

	B1	B2	T1	T2	x_{Noise}
B1	1.00	1.00	0.20	0.25	0.089
B2	1.00	1.00	0.20	0.25	0.089
T1	5.00	5.00	1.00	2.00	0.503
T2	4.00	4.00	0.50	1.00	0.318

Noise level is essentially the same for alternatives B1 and B2. In fact, the only difference between these alternatives is the level of the liquid products separation.

A similar consideration is valid in the case of a comparison between T1 and T2, however the noise level is slightly higher in the second case due to the presence of additional plant utilities (district heating).

Finally, the impact of noise on local populations is stronger in Site B alternatives: in this case the building of a new plant occurs in an area, located less than $3km$ from houses, where there are not already other industries. At the contrary, in the Site T case the plant is added to an already existent factory which is about $10km$ from the city.

Impact during construction

	B1	B2	T1	T2	x_{Const}
B1	1.00	1.00	0.14	0.25	0.072
B2	1.00	1.00	0.14	0.25	0.072
T1	7.00	7.00	1.00	4.00	0.621
T2	4.00	4.00	0.25	1.00	0.235

Impact during construction is stronger in alternatives B1 and B2: in these cases the construction site occupies an area of about $1.5km^2$ near the city and necessary materials are transported through the city, whereas the construction site is smaller and farther from residential areas in T1 and T2. The construction of the pipelines has approximately the same temporary *impact* in all alternatives considering the fact that crossed territories are uninhabited.

Between T1 and T2, it is clear that T2 has a moderately stronger *impact* than T1 because the construction of a new district heating section is required.

Impact on ecosystem

	B1	B2	T1	T2	x_{Ecosys}
B1	1.00	1.00	2.00	2.00	0.333
B2	1.00	1.00	2.00	2.00	0.333
T1	0.50	0.50	1.00	1.00	0.167
T2	0.50	0.50	1.00	1.00	0.167

B1 and B2 held the lowest *Impact on ecosystem* (which is more or less the same for both).

The *impact* is the same between T1 and T2, too, but in this case is slightly stronger because of the greater length of the pipeline. It is reasonable to assume that the *impact* is only slightly higher despite the fact that in this case pipeline length is $800km$ (versus $600km$ in the Site B alternatives) because of the vastness of involved territories and the absence of other anthropic interventions.

5.3.3 Social dimension

Number of local employees

	B1	B2	T1	T2	x_{Empl}
B1	1.00	0.84	4.22	4.22	0.376
B2	1.19	1.00	5.00	5.00	0.446
T1	0.24	0.20	1.00	1.00	0.089
T2	0.24	0.20	1.00	1.00	0.089

Heat connections increase

	B1	B2	T1	T2	x_{Heat}
B1	1.00	1.00	1.00	0.13	0.091
B2	1.00	1.00	1.00	0.13	0.091
T1	1.00	1.00	1.00	0.13	0.091
T2	8.00	8.00	8.00	1.00	0.727

Impact on health

	B1	B2	T1	T2	x_{Health}
B1	1.00	1.00	0.33	0.20	0.096
B2	1.00	1.00	0.33	0.20	0.096
T1	3.00	3.00	1.00	0.33	0.249
T2	5.00	5.00	3.00	1.00	0.558

The higher *impact* in this case occurs in B1 and B2: in these alternatives a new industrial plant is placed near a city, therefore air pollution levels increase in the city. On the other hand, Site B is a small city, far away from large industrial centres, where air quality is quite good, so that the *impact* of the new plant is not extreme.

T2 *impact* is the lowest among the alternatives: the new plant is added to a bigger petrochemical previous-existent area located quite far from cities and the realization of district heating causes the abatement of pollutants in some residential areas in Site T.

The *impact* of the remaining alternative reaches an intermediate level because of the absence of the positive impact of district heating.

5.4 Indicators weights evaluation

Also a weight for each indicator is obtained through pairwise comparisons. Applied procedure is analogous to that used to fill qualitative indicators matrices.

Pairwise comparisons are performed between indicators of the same level, referring to the respective upper level.

The considerations made in order to assign the submitted values and the resultant matrices are reported in next paragraphs starting from lowest level.

5.4.1 Lowest level matrices

Air pollution matrix

	1)	2)	$\mathbf{x}_a$
1) CO_{2equi}	1.00	1.00	0.500
2) NOx	1.00	1.00	0.500

The matrix is the result of a pairwise comparison between the two active sub-indicators referring to air: CO_{2equi} and NOx. In this case the two indicators have equal importance, because CO_{2equi} takes into account a global effect while NOx takes into account a local effect.

5.4.2 Third level matrices

Economic matrix

	1)	$\mathbf{x}_{Eco}$
1) IRR	1.00	1.000

It is obvious that IRR's weight is equal to one since IRR is the only active economic indicator.

Environmental matrix

	1)	2)	3	4)	5)	6)	$\mathbf{x}_{Env}$
1) Soil	1.00	0.50	0.14	1.00	0.25	0.20	0.045
2) H_2O	2.00	1.00	0.17	2.00	0.33	0.25	0.071
3) Air	7.00	6.00	1.00	7.00	4.00	2.00	0.421
4) Noise	1.00	0.50	0.14	1.00	0.25	0.17	0.044
5) Construction	4.00	3.00	0.25	4.00	1.00	0.33	0.145
6) Ecosystem	5.00	4.00	0.50	6.00	3.00	1.00	0.274

Soil and *Noise* have the lowest weights: *Soil consumption* have poor importance in a territory wide and unpopulated as Siberia is; *Noise* have poor importance, too, because areas very close to facilities are not densely populated in all the alternatives.

Also *Water consumption* has not a very strong importance in the context of the project because of a high availability of this resource. However a comparison between *Water* and *Soil consumption* assign as result a slightly higher importance to the first one.

Impact during construction is more weighty because considers population discomfort. On the other hand the weight of this indicator should not be very strong because the effect is temporary.

Impact on ecosystem is in general a very important indicator because reflects the impact of a project on local environmental balances, but in this specific project it is supposed that no sensible areas are involved, and new construction extent is very small compared to the size of the surrounding territory. For these reasons the indicator is "only" of very stronger importance than *Soil consumption.*

Consequently, *Air pollution* obtains the greatest weight.

Social matrix

	1)	2)	3)	$\mathbf{x}_{Soc}$
1) Local employees	1.00	2.00	0.17	0.151
2) Heat connections	0.50	1.00	0.14	0.091
3) Impact on health	6.00	7.00	1.00	0.758

Heat connections increase gets the lowest weight because in this project district heating determines only a slight increment of local populations living conditions.

The indicator *Number of local employees* certainly has higher importance in this context, even if the difference in terms of weight is slight in the considered areas: as a matter of facts the level of unemployment is not very high. Therefore *Impact on health* is the most important indicator, and a pairwise comparison between this indicator and *Heat connections increase* suggests that importance of the first is stronger than that of the second.

5.4.3 Second level matrix

Goal	1)	2)	3)	$\mathbf{x}_g$
Economic	1.00	1.00	1.00	0.333
Environmental	1.00	1.00	1.00	0.333
Social	1.00	1.00	1.00	0.333

Each main criterion, i.e. each dimension of sustainability, has the same importance than others. Hence the same weight is assigned to each one.

5.5 Partial performance matrices

Partial performance matrices are the result of the combination of priority vectors as explained in section 4.5. Matrices are listed below, starting as usual from the lowest hierarchical level and following the main branches of the hierarchy.

5.5.1 Economic branch

$$[\mathbf{W}_{Eco}] = [\mathbf{x}_{IRR}] = \begin{bmatrix} 0.184 \\ 0.056 \\ 0.394 \\ 0.365 \end{bmatrix} \tag{5.3}$$

5.5.2 Environmental branch

$$[\mathbf{W}_{Air}] = \left[\begin{array}{c|c} \mathbf{x}_{CO_2} & \mathbf{x}_{NO_x} \end{array}\right] = \begin{bmatrix} 0.246 & 0.241 \\ 0.064 & 0.080 \\ 0.242 & 0.198 \\ 0.448 & 0.481 \end{bmatrix} \tag{5.4}$$

$$\mathbf{x}_{AirPoll} = [\mathbf{W}_{Air}] \cdot \mathbf{x}_a = \begin{bmatrix} 0.243 \\ 0.072 \\ 0.220 \\ 0.464 \end{bmatrix} \tag{5.5}$$

$$\begin{aligned} [\mathbf{W}_{Env}] &= \left[\begin{array}{c|c|c|c|c|c} \mathbf{x}_{Soil} & \mathbf{x}_{Water} & \mathbf{x}_{AirPoll} & \mathbf{x}_{Noise} & \mathbf{x}_{Const} & \mathbf{x}_{Ecosys} \end{array}\right] = \\ &= \begin{bmatrix} 0.417 & 0.236 & 0.243 & 0.089 & 0.072 & 0.333 \\ 0.417 & 0.069 & 0.072 & 0.089 & 0.072 & 0.333 \\ 0.083 & 0.347 & 0.220 & 0.503 & 0.621 & 0.167 \\ 0.083 & 0.347 & 0.464 & 0.318 & 0.235 & 0.167 \end{bmatrix} \end{aligned} \tag{5.6}$$

5.5.3 Social branch

$$[\mathbf{W}_{Soc}] = \left[\begin{array}{c|c|c} \mathbf{x}_{Empl} & \mathbf{x}_{Heat} & \mathbf{x}_{Health} \end{array}\right] = \begin{bmatrix} 0.376 & 0.091 & 0.096 \\ 0.446 & 0.091 & 0.096 \\ 0.089 & 0.091 & 0.249 \\ 0.089 & 0.727 & 0.558 \end{bmatrix} \tag{5.7}$$

5.5.4 Priority vectors of partial performance matrices

$$\mathbf{x}_{Economic} = [\mathbf{W}_{Eco}] \cdot \mathbf{x}_{Eco} = \begin{bmatrix} 0.184 \\ 0.056 \\ 0.394 \\ 0.365 \end{bmatrix} \tag{5.8}$$

$$\mathbf{x}_{Environmental} = [\mathbf{W}_{Env}] \cdot \mathbf{x}_{Env} = \begin{bmatrix} 0.244 \\ 0.158 \\ 0.279 \\ 0.320 \end{bmatrix} \tag{5.9}$$

$$\mathbf{x}_{Social} = [\mathbf{W}_{Soc}] \cdot \mathbf{x}_{Soc} = \begin{bmatrix} 0.138 \\ 0.149 \\ 0.211 \\ 0.502 \end{bmatrix} \tag{5.10}$$

5.6 Final results

Aggregating the three priority vectors of the main criteria and multiplying the resultant matrix by $\mathbf{x}_g$ the Global Priority Vector (GPV) is obtained.

$$[\mathbf{W}_{Goal}] = \left[\begin{array}{c|c|c} \mathbf{x}_{Economic} & \mathbf{x}_{Environmental} & \mathbf{x}_{Social} \end{array}\right] = \begin{bmatrix} 0.184 & 0.244 & 0.138 \\ 0.056 & 0.158 & 0.149 \\ 0.394 & 0.279 & 0.211 \\ 0.365 & 0.320 & 0.502 \end{bmatrix} \tag{5.11}$$

$$\mathbf{x}_{Goal} = [\mathbf{W}_{Goal}] \cdot \mathbf{x}_g = \begin{bmatrix} 0.189 \\ 0.121 \\ 0.295 \\ 0.396 \end{bmatrix} \tag{5.12}$$

Therefore, the resulting final ranking of alternatives is the subsequent:

Alternative	Score	Ranking
B1	0.189	3
B2	0.121	4
T1	0.295	2
T2	0.396	1

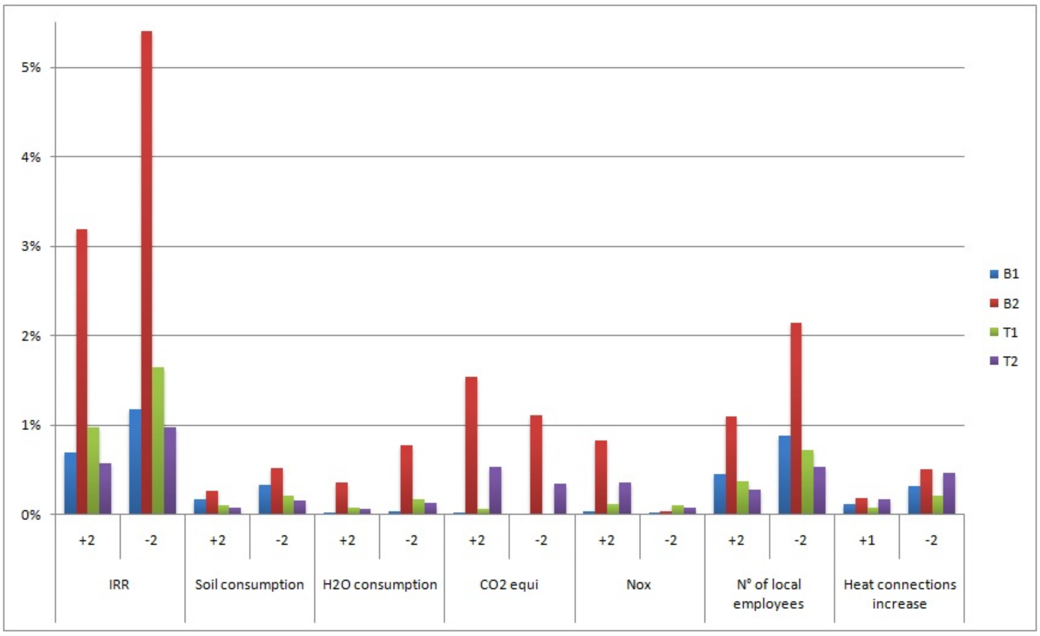

Figure 5.8: Percentage change compared to the base case

5.7 Verification and validation

5.7.1 Sensitivity analysis

A sensitivity analysis was performed to check the stability of the solution.

Two kinds of simulations were adopted:

- Firstly, a change of the maximum value of the normalization scale of quantitative indicators was executed.
- A second test was obtained varying the weights assigned in each qualitative pairwise comparison matrix. The test was not performed with matrices filled in starting from quantitative data because in this case the result does not depend on subjective aspects of the decision-makers.

In the first simulation, the maximum normalization value was changed in a range of ±2 compared to the weight assigned in the base case. The change was made once for each quantitative active indicator.

Diagram in figure 5.8 returns graphically the absolute value of the result by the percentage change compared to the base case. The variation is always included in a range of 6% and is less than 2% except in three cases. In any case the original ranking is maintained with a wide margin. Hence, the result is not strictly dependent from the assignment of this parameter in a range of approximately 20%.

Due to the complexity of implementation of an algorithm in *Excel*, the second kind of simulation is based on the sensitivity analysis tool in the *Super Decisions* software (introduced in section 4.5). The analysis was conduced both varying the weight of each indicator with respect to its dimension (diagrams in figures from 5.9 to 5.11) and the weight of each alternative with respect to each qualitative indicator[7] (diagrams in figures from 5.12 to 5.15).

Results are shown in diagrams: the weight of the indicator (or alternative) is on the horizontal axis and the result for each alternative on the vertical axis. A vertical line indicates the weight that the analysed parameter has in the base case.

In some cases, despite the lines that represent the value of each alternative varying the weight of an indicator are almost always not parallel, the ranking of the alternatives is the same for any variation of the weight itself (for example this is the case of the diagram in figure 5.9a or 5.10b).

At the contrary, in other cases, a change in the ranking is possible by varying the weight of an alternative respect to the considered indicator, but in all cases this happens only with a very high variation of the weight (e.g. in diagrams in figures 5.10a or 5.10e).

The results lead to the conclusion that the stability of the solution is confirmed in a range always wider than the reasonable uncertainty range of the decision-maker.

Therefore, it is possible to assert that in all probability the resulting score of alternatives would have been about the same[8] even though the qualitative pairwise comparison matrices had been drawn up by real decision-makers, assuming that they start from assumptions not too different from those applied by the authors.

5.7.2 Results including a flaring-based alternative

It is interesting to add a fifth alternative to the four actually considered by *Techint* and the client to check the response of the model. In particular this alternative contemplates the possibility of not recovering at all the associated gas, that is completely flared.

All values of quantitative indicators for this additional alternative were evaluated in the same manner as previous (considering a stack combustion efficiency of 85% [83]) except IRR, assumed to be equal to zero. At the contrary, different values of the normalization maximum were selected because of a wider range of values for each indicator.

Table 5.5 shows normalized values of these indicators.

Pairwise comparisons among indicators with respect to their dimension are the same as the ones used previously, too. As a matter of facts the evaluation of these matrices depends upon the local context but do not depend upon the alternatives[9].

At the contrary, pairwise comparisons of the alternatives with respect to each indicator obviously should change when an alternative is added. New values that fill in these matrices were derived using the same considerations already made with regard to the four alternatives that recover gas, but taking into account also the comparison with the fifth alternative.

In particular, this alternative has better performances than other with regard to *Impact during construction* (it only needs the construction of flares stacks) but significantly worse performances with regard to the other qualitative indicators[10]. Filled in matrices are shown in Appendix D.

Table 5.6 quotes the final results of this case and the results of the base case placed side by side.

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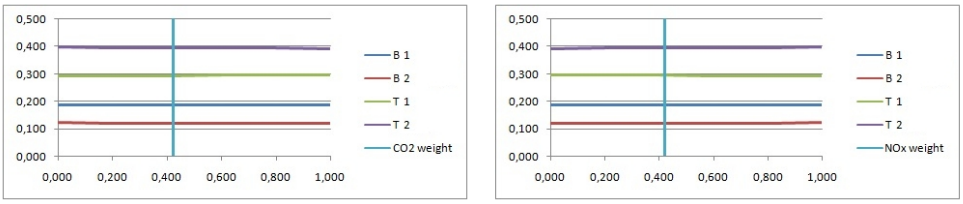
[7] Obviously varying the weight of alternatives within quantitative indicators makes little sense, since the decision-makers do not affect the value of these indicators with a subjective assessment.

[8] Therefore, the ranking would have been exactly the same.

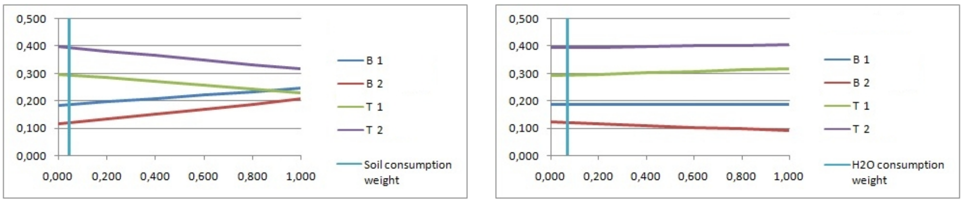
[9] For example, the importance of the indicator *Soil consumption* depends upon the level of human presence in the considered region and not upon the effective quantity of soil consumed by one of the alternatives.

[10] Comparisons were made under the hypothesis of the presence of some inhabited areas in the vicinity of flaring zones.

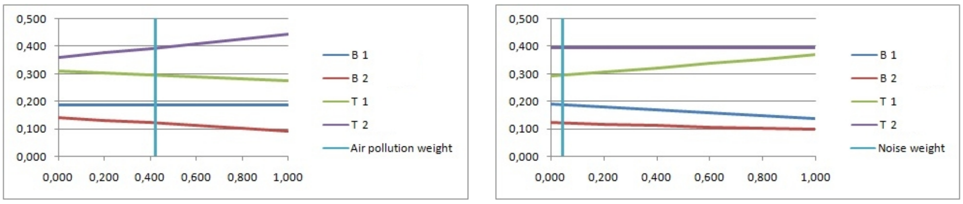


(a) CO_2 (b) NO_x

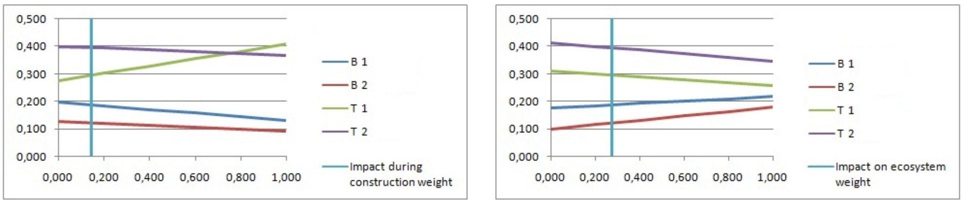
Figure 5.9: Sensitivity analysis for the *Air pollution* indicator



(a) *Soil consumption* (b) *Water consumption*

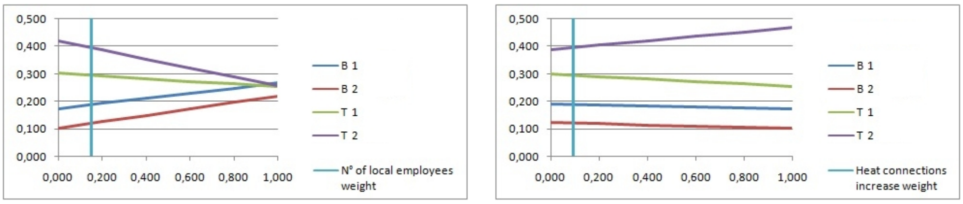


(c) *Air pollution* (d) *Noise*

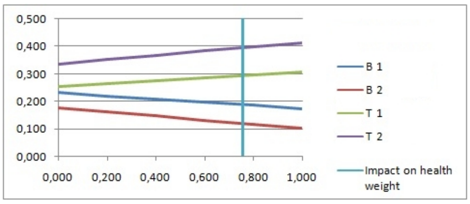


(e) *Impact during construction* (f) *Impact on ecosystem*

Figure 5.10: Sensitivity analysis for Environmental dimension

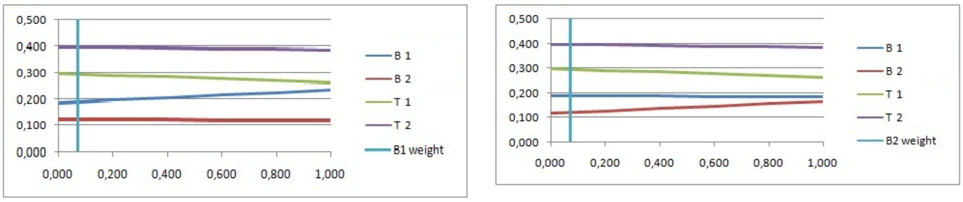


(a) *N*° of local employees (b) *Heat connections increase*

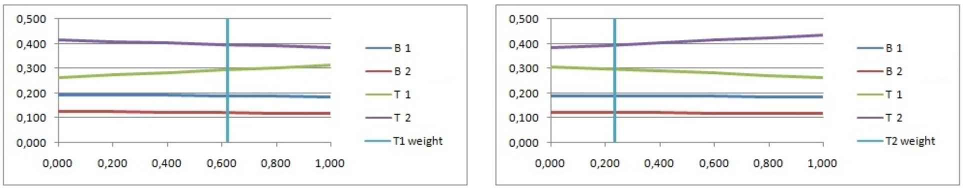


(c) *Impact on health*

Figure 5.11: Sensitivity analysis for Social dimension

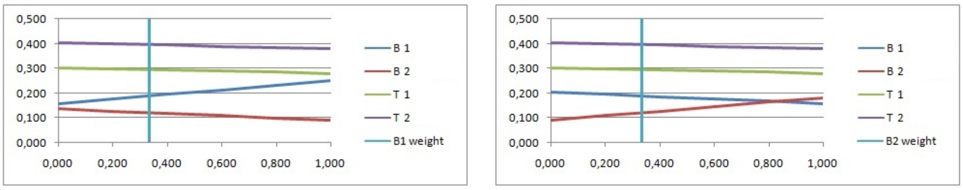


(a) B1 (b) B2

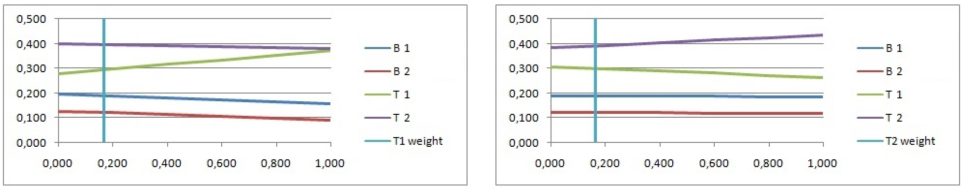


(c) T1 (d) T2

Figure 5.12: Sensitivity analysis for *Impact during construction*

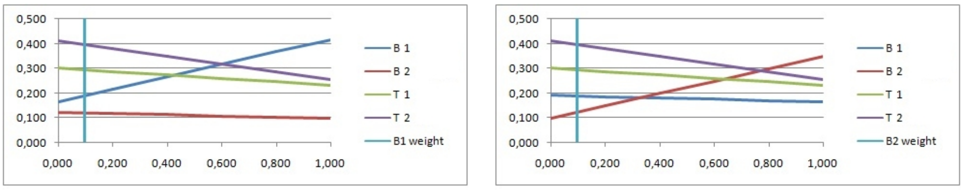


(a) B1 (b) B2

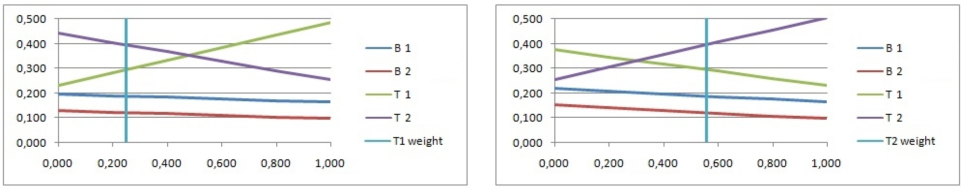


(c) T1 (d) T2

Figure 5.13: Sensitivity analysis for *Impact on ecosystem*

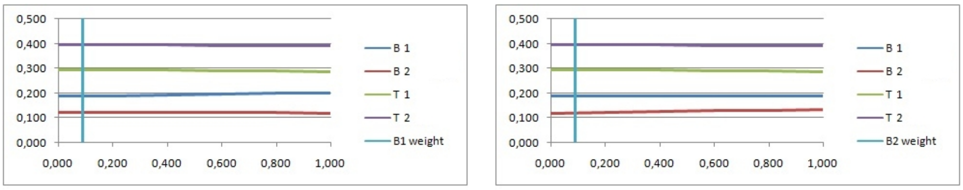


(a) B1 (b) B2

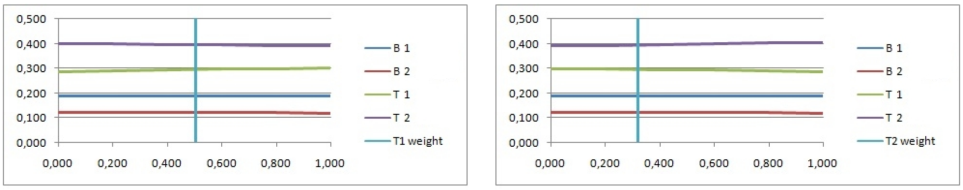


(c) T1 (d) T2

Figure 5.14: Sensitivity analysis for *Health*



(a) B1 (b) B2



(c) T1 (d) T2

Figure 5.15: Sensitivity analysis for *Noise*

	B1	**B2**	**T1**	**T2**	**100% Flared**	***Max***
IRR	7.64	6.68	9.00	8.81	1	*9*
Soil consumption	2.11	2.11	1	1	9	*9*
H_2O consumption	1.48	1	1.81	1.81	9	*9*
CO_{2equi}	8.91	8.85	8.93	9	1	*9*
NOx	8.99	8.98	8.99	9	1	*9*
N° of local employees	8	8	6	6	1	*8*
Heat connections increase	1	1	1	8	1	*8*

Table 5.5: Normalized values assigned to each indicator

Table 5.6: Base-case results vs results adding the alternative “flaring”

Alternative	**Base-case results**	**Results with flaring**	**Ranking**
B1	0.189	0.193	3
B2	0.121	0.184	4
T1	0.295	0.246	2
T2	0.396	0.308	1
Flaring	–	0.069	5

As is logical to expect, the new alternative gets the lowest score, and its distance from the penultimate is wide. Scores of other alternatives are closer when the fifth alternative is activated, because their differences are mitigated by the presence of an alternative with indicators which take values on average much worse.

Chapter 6

Conclusions

6.1 An overall recall of the proposed methodology

To summarize the various concepts and give an overview of the proposed methodology, first of all the various logical steps of the process that lead to choosing the best alternative from a situation in which the gas is burned are retraced. Steps are highlighted in the flowchart in figure 6.1.

1. Starting from a situation where associated gas is flared, firstly it is necessary to select technologies and processes that are eligible from a purely technical point of view. Most common technologies and processes among which is possible make a selection have been analyzed in chapter 2.
2. Once selected eligible technologies and processes, the second step is to proceed with the definition of some alternatives and the realization of a pre-feasibility study by the gas producers. The study aims to verify the overall technical feasibility of alternatives and provides necessary data for the subsequent analysis.
3. A third step is AHP model setting: depending on the context and the alternatives, non-relevant indicators in the AHP model should be disabled.
4. At this point, pairwise comparison matrices referring to both qualitative and quantitative indicators are filled in. In the case of more than one stakeholder (i.e. almost always), each of them fills in a copy of the matrices of qualitative indicators. Priority vectors obtained by each stakeholder are aggregated according to the weight assigned to each stakeholder.
5. Once all parameters of the model have been set, each alternative gets a score, and it is therefore possible to define a ranking.
6. Sensitivity analysis ensures the stability of the solution within the range established by decision-makers.
7. The result of the model obviously has no absolute validity, and can certainly be affected by several errors. Therefore, the ranking should be discussed in detail and critically by decision makers. If the result is not considered acceptable by most decision-makers, AHP analysis must be repeated taking into account the weaknesses that emerged from the discussion.

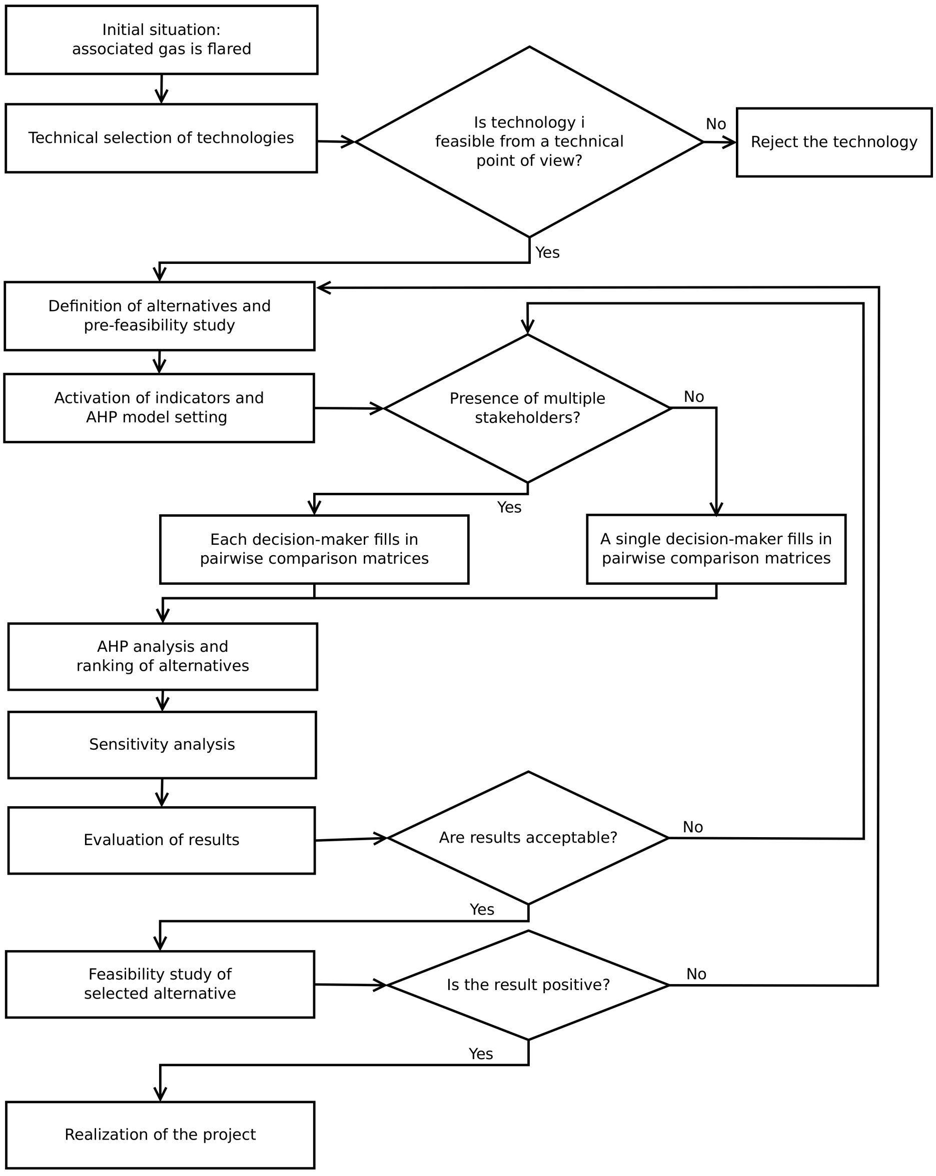


Figure 6.1: Main steps of the decision process

Table 6.1: Alternatives summary

Alternative	Wells distance	Products
B1	$600km$	NG; C_{3+}
B2	$600km$	NG; C_3; C_4; C_{5+}
T1	$800km$	NG; C_{3+}
T2	$800km$	NG; C_{3+}; Heat recovery

8. If instead an agreement is reached, the producer goes on with the realization of a detailed feasibility study. If the result of the study is negative, a redefinition of alternatives is necessary and the process must be repeated.

9. If the result of the study is positive, the project can be realized.

6.2 AHP model results vs real choice: some considerations starting from the case study

Before describing achieved results, a summary of the considered alternatives is shown in table 6.1.

6.2.1 Partial results

Some partial results related to the three dimensions of sustainability (Economic, Environmental, Social), and therefore to the three homonyms main criteria, can be displayed in the *Excel* model with the help of appropriate graphics and allow to make some first considerations.

A first series of diagrams (figure 6.2) shows the priority of each alternative with respect to each indicator. With regard to the Economic dimension it is clear that alternative T1 is the best one, followed by alternative T2, while alternative B2 is the worst[1].

In the Environmental dimension the alternative T1 achieves the first position in the indicators *Impact during construction*, *Noise* and *Water consumption* (in this case the result is equal to that of T2). On the contrary, it loses its position as regards *Air pollution* and *Impact on ecosystem.* T2 also obtains the lowest results in the indicators *Soil consumption* and *Impact on ecosystem*, but has the least impact on the air (it reaches the maximum value of *Air pollution*). B2 achieves good results in *Soil consumption* and *Impact on ecosystem*, as well as B1, but has the worst values of the other indicators. The results of the alternative B1 differ from those of B2 only in *Air pollution* and *Water consumption*, where this alternative gets the highest values of the indicators. Finally, in the Social dimension T2 gets values significantly higher than all other alternatives in *Heat connections increase* and *Impact on health* and the lowest value in the *Number of local employees* indicator as well as T1.

A second set of diagrams shows the distribution of economic, environmental and social scores of each alternative among the various indicators (figure 6.3). Obviously, in the Economic dimension IRR contributes to the score with a share of 100% for each alternative, while, for example, as regards the Environmental dimension, the score of the alternative B1 is composed of 24% by *Impact on ecosystem*, of 31% by *Soil consumption* and of 17%

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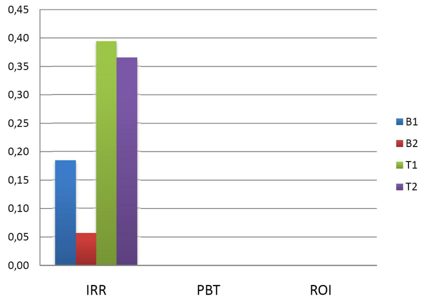
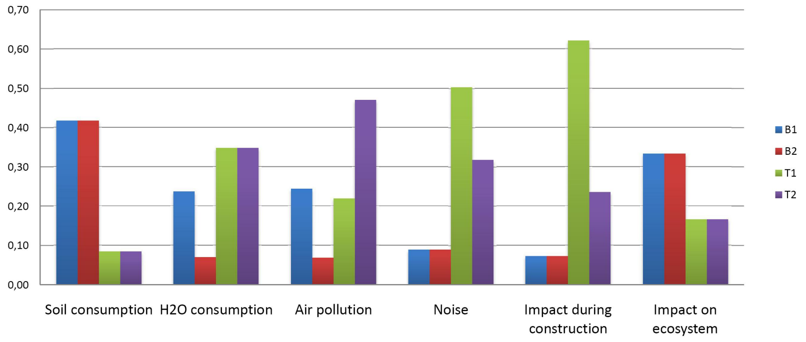
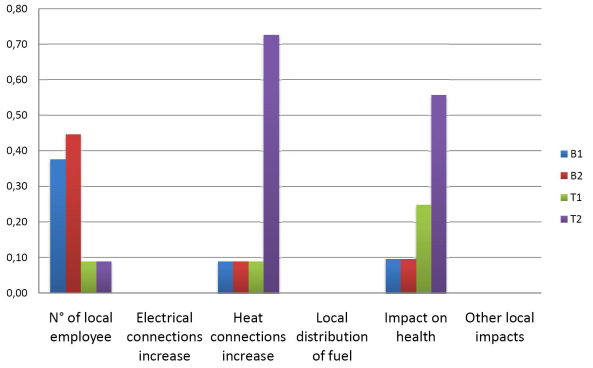
[1] Therefore, it is clear that a decision based only on the parameter IRR involves T1 is chosen as the best alternative.



(a) Economic dimension diagram

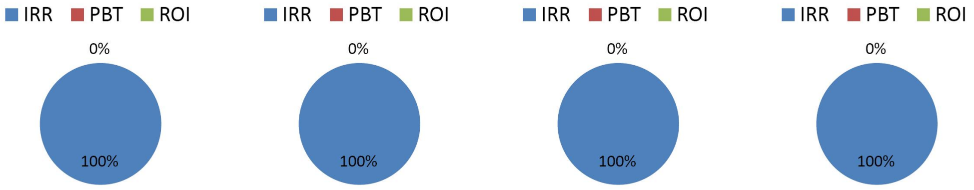


(b) Environmental dimension diagram

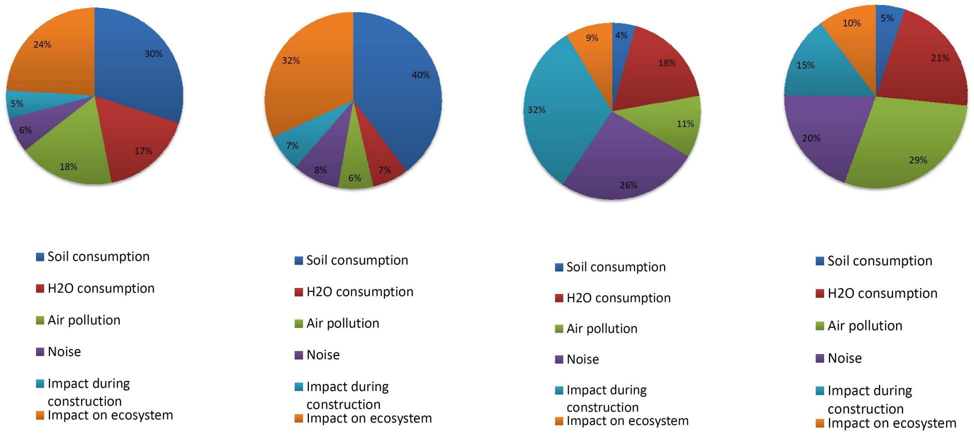


(c) Social dimension diagram

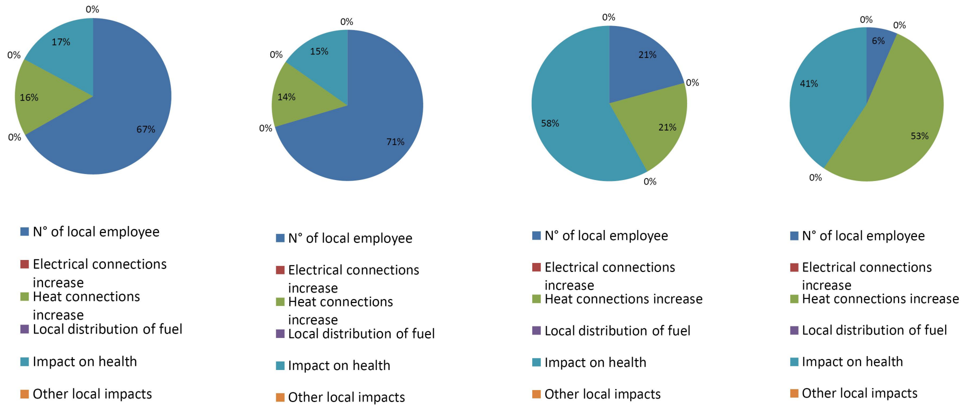
Figure 6.2: Priority of each alternative vs lower levels



(a) Economic scores (B1, B2, T1, T2, from left to right)



(b) Environmental scores (B1, B2, T1, T2, from left to right)



(c) Social scores (B1, B2, T1, T2, from left to right)

Figure 6.3: Economic, environmental and social scores of each alternative among the various indicators

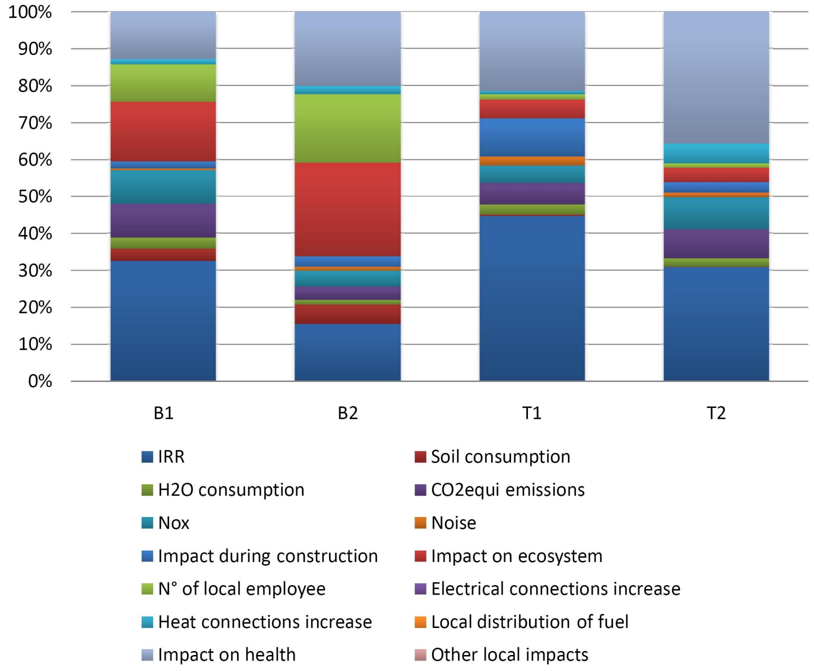


Figure 6.4: Share of the overall score among all indicators (100 basis)

by *H_2O consumption* and *Air pollution*. Instead, *Noise* and *Impact during construction* cover a slice respectively of 6% and 5%.

Similar considerations can be made for other alternatives, both as regards the Environmental dimension and the social one.

The overall analysis of these diagrams leads to stress again the fact that each alternative is characterized by peculiar strengths and weaknesses. This is in general a common characteristic of complex projects such as those concerning the recovery of associated gas, fact that endorses the choice of a multi-attribute decision method.

6.2.2 Final results

The share of the overall score among all the indicators for each alternative is displayed on a percentage basis in the diagram in figure 6.4 and in absolute terms in the diagram in figure 6.5.

From the first diagram to understand how the different scores obtained by the various alternatives for each indicator compose the final score of each of them is easy: to give an example, *Impact on health* contributes greatly to the result obtained by alternative T2.

From diagram in figure 6.5 also the final order is graphically clear: the best solution T2 receives a score of approximately 0.4, followed by T1 with a score of about 0.3. B1 and B2 instead have lower scores.

A comparison between the ranking obtained by applying the model and the real ranking established by *Techint* leads to some interesting conclusions: as table 6.2 shows, results are different because in one case environmental and social parameters are considered, while in the other case the choice was made only on the basis of economic parameters. In particular, the ranking made by *Techint* is based only on IRR in the case of alternatives B1, B2, and

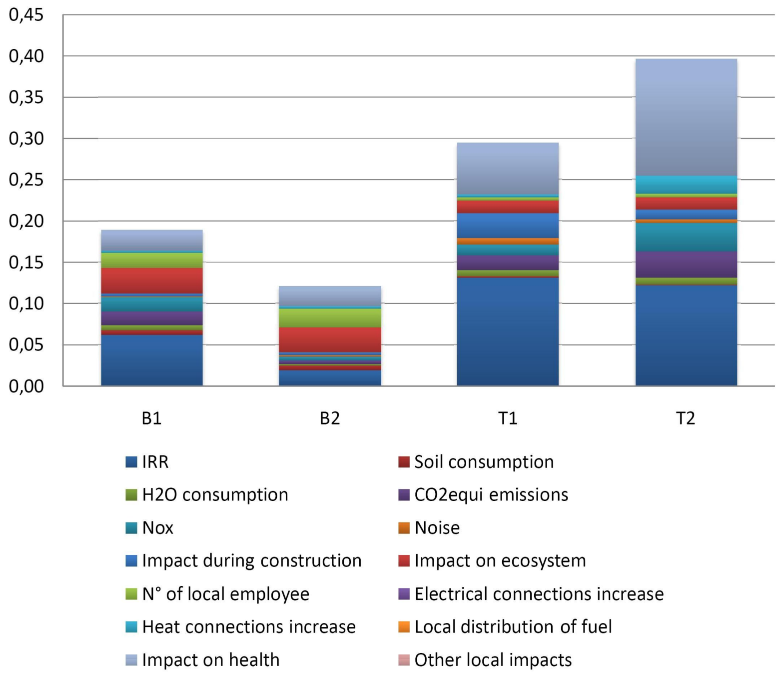


Figure 6.5: Share of the overall score among all indicators (absolute values)

Table 6.2: Model results vs real ranking

Alternative	Model results	Model ranking	*Techint* ranking
B1	0.189	3	2
B2	0.121	4	3
T1	0.295	2	1
T2	0.396	1	4

T1, while alternative T2 was considered the worst since in this case the parameter IRR is worse than in T1 and the construction phase requires more time and resources.

The discrepancy between the two rankings confirms the fact that not always the best alternative from a standpoint of the economic return achieves a good compromise for sustainability. Therefore, the discrepancy confirms also the fact that the evaluation of alternatives should be made considering a number of criteria relating to the three dimensions of sustainability if the goal is to exploit an opportunity to obtain not only an economic improvement, but also an environmental and social one.

6.3 General conclusions

The preliminary analysis of data about gas flaring underlined a serious energy waste and highlighted the consequences that the practice has in terms of sustainability. Causes that led to the spread of this practice are complex, and, as a consequence, the solution of the problem is complex, especially if the goal is to take into account not only economic aspects, but also environmental and social ones.

The presence of various stakeholders is a crucial feature of the problem, therefore it is very important to involve all of them both in the definition of a common strategy and in the identification of possible alternatives in order to obtain a solution acceptable to each one.

Technologies that can be used to recover associated gas and to increase its value are many. Most of them are widely used in the industrial field, and therefore are accompanied by an extensive commercial experience, while some others are still under development. From this point of view, a further development of technologies that can be used in the case of small gas flow rates, such as small-size GTL, will surely provide a valuable help in many situations.

However, in addition to technical-related problems, there are also other problems for which it is not possible to find a solution without the collaboration of the various stakeholders. Therefore, the need of a shared project to obtain a shared solution is once again underlined also by international organization, and first of all by the World Bank, that since a long time deals with the problem and its possible solutions thanks to its initiative, known under the acronym *GGFR*.

Within this context, the purpose of the thesis was to provide an instrument to support and facilitate the elimination of gas flaring by selecting the best alternative among those feasible by a technical point of view. In particular, the choice fell on the development of a model based on the decision method known as Analytic Hierarchy Process, developed by Saaty. Most interesting features of this model are:

- the fact that criteria can be grouped according to the dimension (economic, environmental, social) to which they refer;
- the possibility to use both qualitative and quantitative indicators;
- the possibility to consider various stakeholders in the decision process;
- the simple way to obtain a comparison among alternatives.

Clearly, the model is characterized by some weaknesses, too. The most important one is the *rank reversal* phenomenon which, however, should occur only if the number of alternatives is excessive or if there are very similar alternatives. Moreover, it is clear that the subjectivity of decision-makers can have an impact on the final result. However, this is not a specific weakness of AHP, but an intrinsic feature of every decision method.

The application of the model to a real case study permitted to test the response of the model applied in the specific context of gas flaring reduction and revealed a good stability of the solution. In any case it is necessary to underline the importance for decision-makers to be analysts as well as users.

6.4 Future developments

Some further developments could be the following:

- application of the model to other case studies in order to definitively validate the set of criteria and indicators, eventually adding new ones to those proposed in this work, and to highlight other critical issues that should be removed or taken into account in a successful application of the method to real cases;
- a comparison of the decision method with other ones to confirm the usefulness of the model used.

Appendices

Appendix A

Historical flared gas data

In table A.1 there are the complete data (expressed in billions cubic meters) of associated gas flaring estimated with satellites by NOAA between 1994 and 2010 [84].

Table A.1: Gas flaring data from 1994 to 2010 (billions cubic meters)

Country	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Russia	39	38,14	36,1	33,74	37,53	36,51	40,17	41,42	44,51	52,65	49,64	58,3	50,0	52,3	42,0	46,6	35,24
Nigeria	24,22	27,09	32,5	29,13	25,93	24,15	27,19	26,81	21,01	23,83	22,63	21,3	18,6	16,3	15,5	14,9	15,18
Iran	11,61	10,74	11,55	11,42	9,17	8,78	10,26	9,04	8,81	11,64	11,01	11,7	12,2	10,7	10,8	10,9	11,27
Iraq	2,83	2,99	2,88	4,71	5,39	6,39	7,01	7,14	6,31	6,44	7,62	7,0	7,2	6,7	7,1	8,1	9,13
Algeria	8,33	9,24	9,39	7,81	7,05	6,77	7,6	6,11	5,25	6,27	5,78	5,7	6,4	5,6	6,2	4,9	5,4
Angola	3,63	4,51	5,76	6,05	6,66	6,61	5,94	5,53	5,14	4,87	4,88	4,7	4,0	3,5	3,5	3,4	4,08
Kazakhstan	2,45	2,48	2,75	3,53	4,07	3,5	4,22	4,18	5,95	5,89	5,85	6,2	6,2	5,5	5,4	5,0	3,8
Libya	5,86	6,56	6,87	5,23	4,53	4,13	4,46	3,87	3,69	4,56	4,23	4,6	4,4	3,8	4,0	3,5	3,79
Saudi Arabia	3,19	2,9	3,24	3,62	3,18	2,89	3,31	3,08	3,01	3,62	3,16	3,5	3,8	3,8	3,9	3,6	3,36
Venezuela	1,27	2,19	2,12	2,5	2,9	2,76	3,15	2,64	2,03	1,99	2,22	2,2	2,1	2,2	2,7	2,8	2,83
Mexico	1,49	1,96	2,5	3,31	3,33	2,74	2,86	2,43	1,98	2,11	1,7	1,9	2,1	2,7	3,6	3,0	2,5
Indonesia	5,82	5,12	5,82	6,36	5,48	4,79	4,56	4,63	3,76	3,7	3,18	3,0	3,2	2,6	2,5	2,9	2,27
China	1,99	1,98	2,97	2,89	2,2	2,36	2,52	2,54	2,39	2,76	2,76	3,0	2,9	2,6	2,5	2,4	2,11
Canada	1,12	1,57	1,45	1,42	1,98	1,81	1,86	1,83	1,45	1,59	1,43	1,3	1,7	2,0	1,9	1,8	2,07
USA	3,42	3,25	3,03	3,17	3,01	2,64	2,42	2,42	2,37	2,63	1,96	2,2	2,0	2,1	2,3	2,0	2,06
Uzbekistan	0,96	1,14	1,4	1,28	1,32	0,98	1,32	1,93	2,69	2,32	2,12	2,7	2,9	2,1	2,7	1,7	1,87
Qatar	1,08	0,98	1,47	2,87	2,75	2,92	3,35	2,75	2,63	3,08	2,76	2,3	2,3	2,4	2,3	2,2	1,85
Oman	1,71	1,97	2,1	2,41	1,98	2,14	2,24	2,39	2,48	2,93	2,77	2,6	2,3	2,0	2,0	1,9	1,77
Kuwait	2,01	1,76	1,88	2,18	1,65	1,53	1,87	1,66	1,8	2,35	2,2	2,3	2,3	2,0	1,7	1,6	1,49
Malaysia	1,39	1,24	1,5	1,79	1,35	1,34	1,38	1,37	1,39	1,77	1,78	1,8	1,9	1,8	1,9	1,9	1,47
Top-20	123,38	127,82	137,28	135,43	131,46	125,76	137,7	133,77	128,66	147	139,68	148,17	138,49	132,72	124,45	125,1	113,54
Global	149,23	154,97	164,65	163,28	158,6	153,32	164,9	159,37	151,3	170,85	162,62	172	161	154	146	147	134

Appendix B

Data of fields considered in the Russian project

In table B.1 data about estimated raw gas composition from 2015 to 2030 for the fields considered by *Techint* in the Russian project are shown. In table B.2 the type and the development status of each field are available.

Table B.1: Composition of raw gas from fields

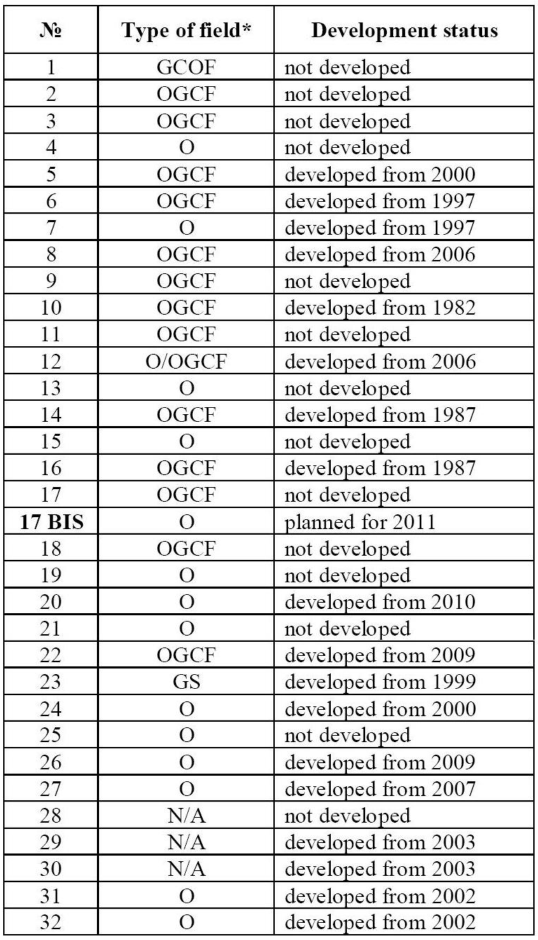
(a) From 2015 to 2022

	Composition								
Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	
CO2	29,2	33,8	32,6	32,1	31,5	32,5	34,5	37,4	MM Sm3 / y
N2	31,3	40,3	38,4	36,8	35,3	35,4	36,0	37,3	MM Sm3 / y
CH4	1939,6	2422,9	2312,4	2299,4	2290,8	2338,1	2403,7	2480,9	MM Sm3 / y
C2H6	137,4	166,3	162,9	162,6	162,5	165,0	169,7	175,4	MM Sm3 / y
C3H8	122,0	140,1	133,8	132,9	133,4	133,5	136,2	140,0	MM Sm3 / y
iC4H10	30,8	34,7	33,1	33,3	33,8	33,8	34,3	34,9	MM Sm3 / y
nC4H10	51,1	56,4	53,4	53,2	54,1	53,8	54,8	55,5	MM Sm3 / y
C5+	41,4	51,4	47,8	45,5	44,7	42,7	42,0	41,3	MM Sm3 / y

(b) From 2023 to 2030

	Composition								
Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
CO2	37,8	37,1	35,4	32,6	30,1	28,6	25,8	23,5	MM Sm3 / y
N2	37,5	36,3	34,2	30,9	28,3	26,5	23,2	20,3	MM Sm3 / y
CH4	2529,8	2473,3	2329,9	2094,5	1911,6	1807,9	1584,8	1412,5	MM Sm3 / y
C2H6	177,7	175,1	165,3	149,8	137,2	129,5	114,6	102,9	MM Sm3 / y
C3H8	141,2	141,6	135,9	124,0	114,2	109,0	97,3	87,4	MM Sm3 / y
iC4H10	35,2	35,3	34,0	30,8	28,2	27,2	24,3	21,6	MM Sm3 / y
nC4H10	55,7	56,3	54,4	49,3	45,3	43,7	38,9	34,8	MM Sm3 / y
C5+	42,4	46,2	44,6	41,0	38,1	36,6	32,8	29,1	MM Sm3 / y

Table B.2: List of fields (source: *Techint*)



№	Type of field*	Development status
1	GCOF	not developed
2	OGCF	not developed
3	OGCF	not developed
4	O	not developed
5	OGCF	developed from 2000
6	OGCF	developed from 1997
7	O	developed from 1997
8	OGCF	developed from 2006
9	OGCF	not developed
10	OGCF	developed from 1982
11	OGCF	not developed
12	O/OGCF	developed from 2006
13	O	not developed
14	OGCF	developed from 1987
15	O	not developed
16	OGCF	developed from 1987
17	OGCF	not developed
17 BIS	O	planned for 2011
18	OGCF	not developed
19	O	not developed
20	O	developed from 2010
21	O	not developed
22	OGCF	developed from 2009
23	GS	developed from 1999
24	O	developed from 2000
25	O	not developed
26	O	developed from 2009
27	O	developed from 2007
28	N/A	not developed
29	N/A	developed from 2003
30	N/A	developed from 2003
31	O	developed from 2002
32	O	developed from 2002

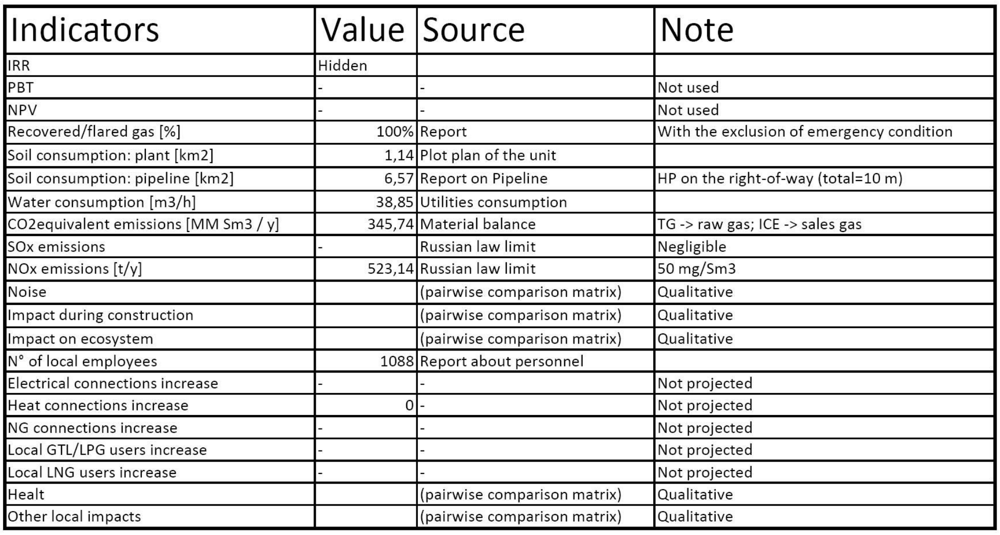
* Notes:
O - oil field
OGCF – oil-gas condensate field
O/OGCF – oil field which can be considered as oil-gas condensate field
GCOF – gas-condensate oil field
GS - gas condensate field
N/A - data not available

Appendix C

Scenarios indicators

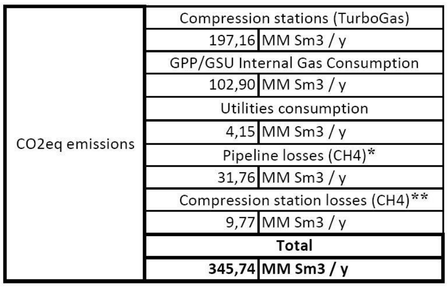
In this appendix: a sum up of indicators, their sources and other notes for each alternative (from table C.1 to table C.13). In table C.14: assumptions and calculation about district heating.

Table C.1: Indicators for alternative B1



Indicators	Value	Source	Note
IRR	Hidden		
PBT	-	-	Not used
NPV	-	-	Not used
Recovered/flared gas [%]	100%	Report	With the exclusion of emergency condition
Soil consumption: plant [km2]	1,14	Plot plan of the unit	
Soil consumption: pipeline [km2]	6,57	Report on Pipeline	HP on the right-of-way (total=10 m)
Water consumption [m3/h]	38,85	Utilities consumption	
CO2equivalent emissions [MM Sm3 / y]	345,74	Material balance	TG -> raw gas; ICE -> sales gas
SOx emissions	-	Russian law limit	Negligible
NOx emissions [t/y]	523,14	Russian law limit	50 mg/Sm3
Noise		(pairwise comparison matrix)	Qualitative
Impact during construction		(pairwise comparison matrix)	Qualitative
Impact on ecosystem		(pairwise comparison matrix)	Qualitative
N° of local employees	1088	Report about personnel	
Electrical connections increase	-	-	Not projected
Heat connections increase	0	-	Not projected
NG connections increase	-	-	Not projected
Local GTL/LPG users increase	-	-	Not projected
Local LNG users increase	-	-	Not projected
Healt		(pairwise comparison matrix)	Qualitative
Other local impacts		(pairwise comparison matrix)	Qualitative

Table C.2: CO_2 indicator calculation for B1

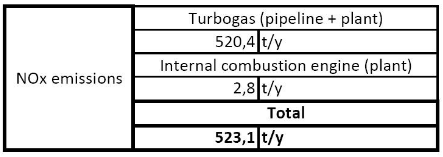


CO2eq emissions	Compression stations (TurboGas)	
	197,16	MM Sm3 / y
	GPP/GSU Internal Gas Consumption	
	102,90	MM Sm3 / y
	Utilities consumption	
	4,15	MM Sm3 / y
	Pipeline losses (CH4)*	
	31,76	MM Sm3 / y
	Compression station losses (CH4)**	
	9,77	MM Sm3 / y
	Total	
	345,74	**MM Sm3 / y**

* Coefficient of losses: $6458 \frac{m^3}{(km \cdot y)}$[85]

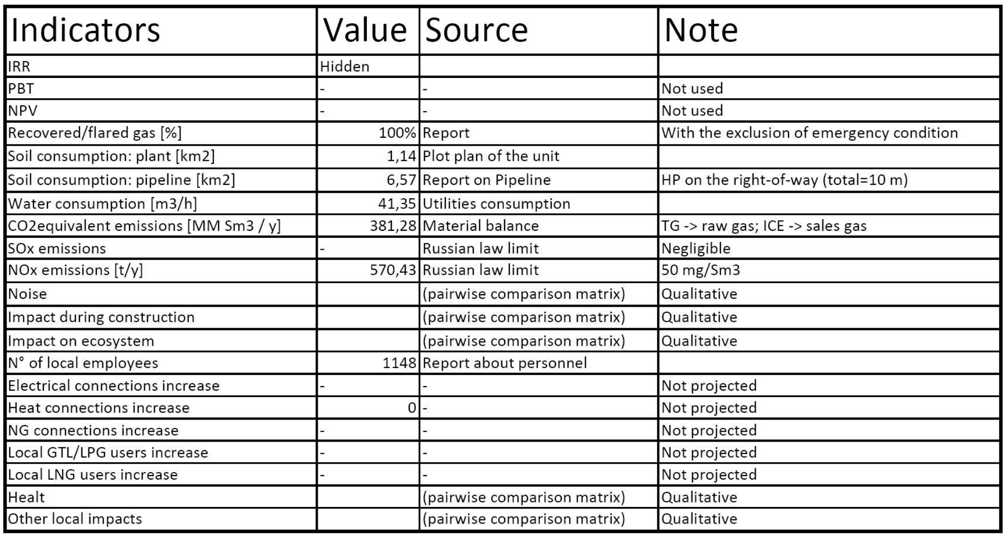
** Coefficient of losses: $21364 \frac{m^3}{(MW \cdot y)}$[86]

Table C.3: NO_x indicator calculation for B1



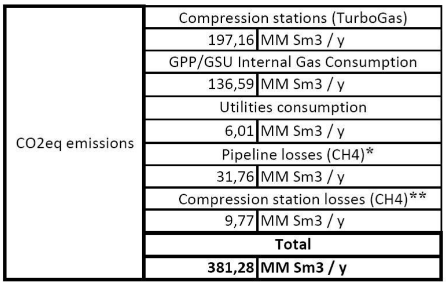
NOx emissions	Turbogas (pipeline + plant)	
	520,4	t/y
	Internal combustion engine (plant)	
	2,8	t/y
	Total	
	523,1	**t/y**

Table C.4: Indicators for alternative B2



Indicators	Value	Source	Note
IRR	Hidden		
PBT	-	-	Not used
NPV	-	-	Not used
Recovered/flared gas [%]	100%	Report	With the exclusion of emergency condition
Soil consumption: plant [km2]	1,14	Plot plan of the unit	
Soil consumption: pipeline [km2]	6,57	Report on Pipeline	HP on the right-of-way (total=10 m)
Water consumption [m3/h]	41,35	Utilities consumption	
CO2equivalent emissions [MM Sm3 / y]	381,28	Material balance	TG -> raw gas; ICE -> sales gas
SOx emissions	-	Russian law limit	Negligible
NOx emissions [t/y]	570,43	Russian law limit	50 mg/Sm3
Noise		(pairwise comparison matrix)	Qualitative
Impact during construction		(pairwise comparison matrix)	Qualitative
Impact on ecosystem		(pairwise comparison matrix)	Qualitative
N° of local employees	1148	Report about personnel	
Electrical connections increase	-	-	Not projected
Heat connections increase	0	-	Not projected
NG connections increase	-	-	Not projected
Local GTL/LPG users increase	-	-	Not projected
Local LNG users increase	-	-	Not projected
Healt		(pairwise comparison matrix)	Qualitative
Other local impacts		(pairwise comparison matrix)	Qualitative

Table C.5: CO_2 indicator calculation for B2

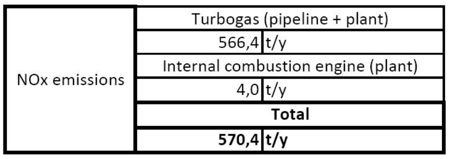


CO2eq emissions	Compression stations (TurboGas)	
	197,16	MM Sm3 / y
	GPP/GSU Internal Gas Consumption	
	136,59	MM Sm3 / y
	Utilities consumption	
	6,01	MM Sm3 / y
	Pipeline losses (CH4)*	
	31,76	MM Sm3 / y
	Compression station losses (CH4)**	
	9,77	MM Sm3 / y
	Total	
	381,28	**MM Sm3 / y**

* Coefficient of losses: $6458\frac{m^3}{(km\cdot y)}$[85]

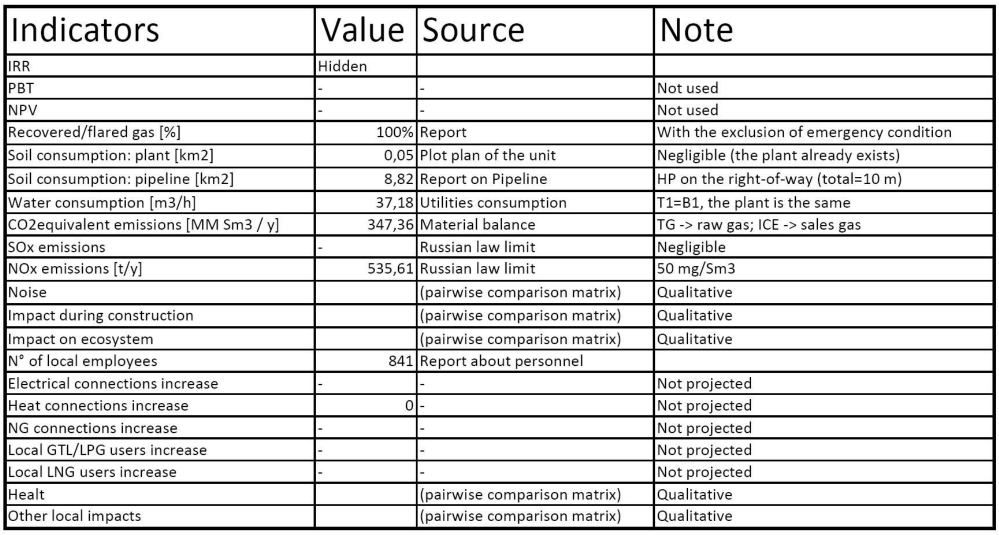
** Coefficient of losses: $21364\frac{m^3}{(MW\cdot y)}$[86]

Table C.6: NO_x indicator calculation for B2



NOx emissions	Turbogas (pipeline + plant)	
	566,4	t/y
	Internal combustion engine (plant)	
	4,0	t/y
	Total	
	570,4	**t/y**

Table C.7: Indicators for alternative T1



Indicators	Value	Source	Note
IRR	Hidden		
PBT	-	-	Not used
NPV	-	-	Not used
Recovered/flared gas [%]	100%	Report	With the exclusion of emergency condition
Soil consumption: plant [km2]	0,05	Plot plan of the unit	Negligible (the plant already exists)
Soil consumption: pipeline [km2]	8,82	Report on Pipeline	HP on the right-of-way (total=10 m)
Water consumption [m3/h]	37,18	Utilities consumption	T1=B1, the plant is the same
CO2equivalent emissions [MM Sm3 / y]	347,36	Material balance	TG -> raw gas; ICE -> sales gas
SOx emissions	-	Russian law limit	Negligible
NOx emissions [t/y]	535,61	Russian law limit	50 mg/Sm3
Noise		(pairwise comparison matrix)	Qualitative
Impact during construction		(pairwise comparison matrix)	Qualitative
Impact on ecosystem		(pairwise comparison matrix)	Qualitative
N° of local employees	841	Report about personnel	
Electrical connections increase	-	-	Not projected
Heat connections increase	0	-	Not projected
NG connections increase	-	-	Not projected
Local GTL/LPG users increase	-	-	Not projected
Local LNG users increase	-	-	Not projected
Healt		(pairwise comparison matrix)	Qualitative
Other local impacts		(pairwise comparison matrix)	Qualitative

Table C.8: CO_2 indicator calculation for T1

CO2eq emissions	Compression stations (TurboGas)	
	204,56	MM Sm3 / y
	GPP/GSU Internal Gas Consumption	
	85,26	MM Sm3 / y
	Utilities consumption	
	3,92	MM Sm3 / y
	Pipeline losses (CH4)*	
	42,63	MM Sm3 / y
	Compression station losses (CH4)**	
	10,99	MM Sm3 / y
	Total	
	347,36	**MM Sm3 / y**

$$* \text{ Coefficient of losses: } 6458\frac{m^3}{(km \cdot y)}[85]$$

$$** \text{ Coefficient of losses: } 21364\frac{m^3}{(MW \cdot y)}[86]$$

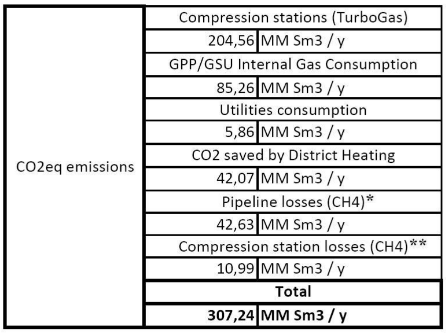
Table C.9: NO_x indicator calculation for T1

NOx emissions	Turbogas (pipeline + plant)	
	533,0	t/y
	Internal combustion engine (plant)	
	2,6	t/y
	Total	
	535,6	**t/y**

Table C.10: Indicators for alternative T2

Indicators	Value	Source	Note
IRR	Hidden		Hypothesizing the ΔIRR with T1
PBT	-	-	Not used
NPV	-	-	Not used
Recovered/flared gas [%]	100%	Report	With the exclusion of emergency condition
Soil consumption: plant [km2]	0,05	Plot plan of the unit	Negligible (the plant already exists)
Soil consumption: pipeline [km2]	8,82	Report on Pipeline	HP on the right-of-way (total=10 m)
Water consumption [m3/h]	37,18	Utilities consumption	T2=B1 because the plant is the same
CO2equivalent emissions [MM Sm3 / y]	307,24	Material balance	TG -> raw gas; ICE -> sales gas
SOx emissions	-	Russian law limit	Negligible
NOx emissions [t/y]	453,04	Russian law limit	50 mg/Sm3
Noise		(pairwise comparison matrix)	Qualitative
Impact during construction		(pairwise comparison matrix)	Qualitative
Impact on ecosystem		(pairwise comparison matrix)	Qualitative
N° of local employees	841	Report about personnel	
Electrical connections increase	-	-	Not projected
Heat connections increase	3405	-	Hypothesis
NG connections increase	-	-	Not projected
Local GTL/LPG users increase	-	-	Not projected
Local LNG users increase	-	-	Not projected
Healt		(pairwise comparison matrix)	Qualitative
Other local impacts		(pairwise comparison matrix)	Qualitative

Table C.11: CO_2 indicator calculation for T2

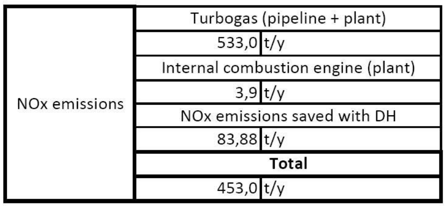


CO2eq emissions	Compression stations (TurboGas)	
	204,56	MM Sm3 / y
	GPP/GSU Internal Gas Consumption	
	85,26	MM Sm3 / y
	Utilities consumption	
	5,86	MM Sm3 / y
	CO2 saved by District Heating	
	42,07	MM Sm3 / y
	Pipeline losses (CH4)*	
	42,63	MM Sm3 / y
	Compression station losses (CH4)**	
	10,99	MM Sm3 / y
	Total	
	307,24	**MM Sm3 / y**

$$\text{* Coefficient of losses: } 6458\frac{m^3}{(km \cdot y)}[85]$$

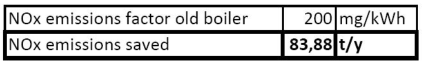
$$\text{** Coefficient of losses: } 21364\frac{m^3}{(MW \cdot y)}[86]$$

Table C.12: NO_x indicator calculation for T2



NOx emissions	Turbogas (pipeline + plant)	
	533,0	t/y
	Internal combustion engine (plant)	
	3,9	t/y
	NOx emissions saved with DH	
	83,88	t/y
	Total	
	453,0	t/y

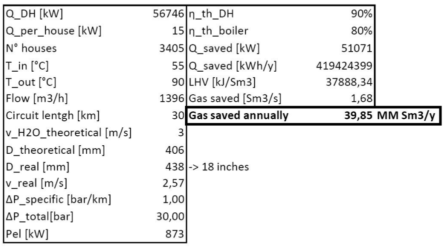
Table C.13: NO_x avoided thanks to district heating for T2



NOx emissions factor old boiler	200	mg/kWh
NOx emissions saved	**83,88**	**t/y**

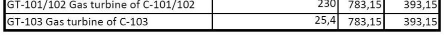
Table C.14: Data for district heating (alternative T2)

(a) Calculation



Q_DH [kW]	56746	η_th_DH	90%	
Q_per_house [kW]	15	η_th_boiler	80%	
N° houses	3405	Q_saved [kW]	51071	
T_in [°C]	55	Q_saved [kWh/y]	419424399	
T_out [°C]	90	LHV [kJ/Sm3]	37888,34	
Flow [m3/h]	1396	Gas saved [Sm3/s]	1,68	
Circuit lentgh [km]	30	**Gas saved annually**	**39,85**	**MM Sm3/y**
v_H2O_theoretical [m/s]	3			
D_theoretical [mm]	406			
D_real [mm]	438	-> 18 inches		
v_real [m/s]	2,57			
ΔP_specific [bar/km]	1,00			
ΔP_total[bar]	30,00			
Pel [kW]	873			

(b) Gas turbine data



Description	Volumes [m3@510/s]	TOT [K]	Tfinal [K]
GT-101/102 Gas turbine of C-101/102	230	783,15	393,15
GT-103 Gas turbine of C-103	25,4	783,15	393,15

Appendix D

Pairwise comparisons matrices

This appendix shows the pairwise comparisons matrices of qualitative (on a blue background) and quantitative (on a white background) indicators used in the Russian project including the alternative “Flaring” (from table D.1 to table D.11).

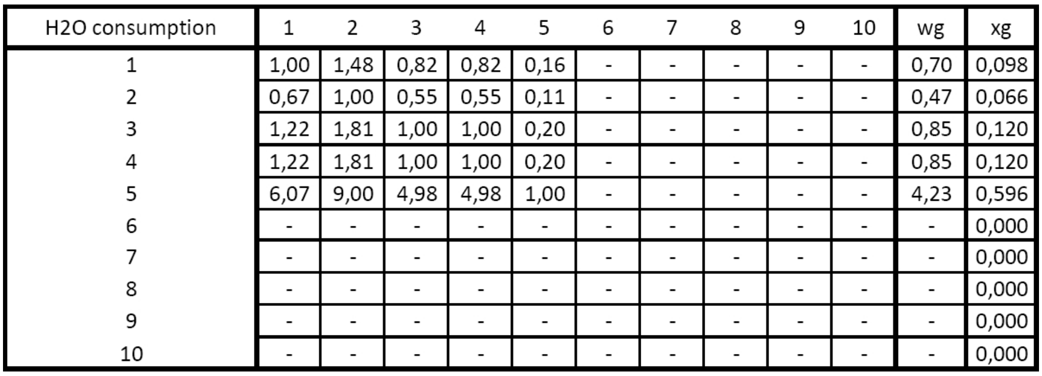
Table D.1: IRR

IRR	1	2	3	4	5	6	7	8	9	10	wg	xg
1	1,00	1,12	0,85	0,87	5,98	-	-	-	-	-	1,38	0,228
2	0,90	1,00	0,76	0,78	5,35	-	-	-	-	-	1,23	0,204
3	1,17	1,31	1,00	1,02	7,00	-	-	-	-	-	1,61	0,267
4	1,15	1,28	0,98	1,00	6,86	-	-	-	-	-	1,58	0,262
5	0,17	0,19	0,14	0,15	1,00	-	-	-	-	-	0,23	0,038
6	-	-	-	-	-	-	-	-	-	-	-	0,000
7	-	-	-	-	-	-	-	-	-	-	-	0,000
8	-	-	-	-	-	-	-	-	-	-	-	0,000
9	-	-	-	-	-	-	-	-	-	-	-	0,000
10	-	-	-	-	-	-	-	-	-	-	-	0,000

Table D.2: Soil consumption

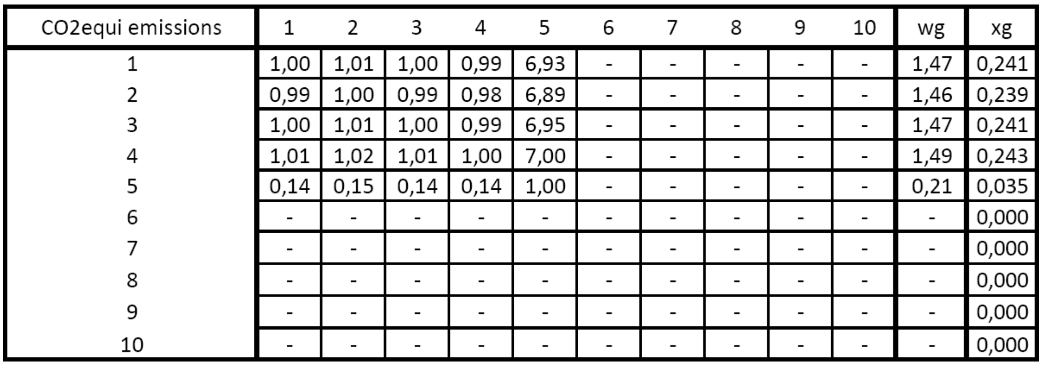
Soil consumption	1	2	3	4	5	6	7	8	9	10	wg	xg
1	1,00	1,00	1,55	1,55	0,31	-	-	-	-	-	0,94	0,154
2	1,00	1,00	1,55	1,55	0,31	-	-	-	-	-	0,94	0,154
3	0,64	0,64	1,00	1,00	0,20	-	-	-	-	-	0,61	0,099
4	0,64	0,64	1,00	1,00	0,20	-	-	-	-	-	0,61	0,099
5	3,22	3,22	5,00	5,00	1,00	-	-	-	-	-	3,04	0,495
6	-	-	-	-	-	-	-	-	-	-	-	0,000
7	-	-	-	-	-	-	-	-	-	-	-	0,000
8	-	-	-	-	-	-	-	-	-	-	-	0,000
9	-	-	-	-	-	-	-	-	-	-	-	0,000
10	-	-	-	-	-	-	-	-	-	-	-	0,000

Table D.3: H_2O consumption



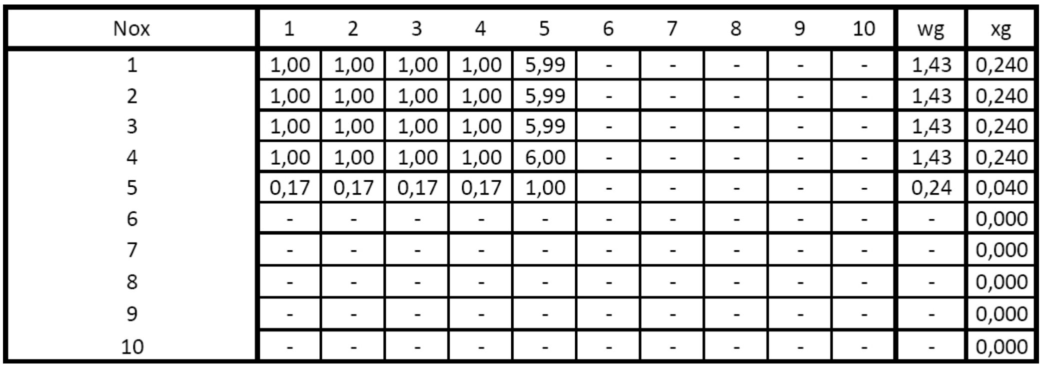
H2O consumption	1	2	3	4	5	6	7	8	9	10	wg	xg
1	1,00	1,48	0,82	0,82	0,16	-	-	-	-	-	0,70	0,098
2	0,67	1,00	0,55	0,55	0,11	-	-	-	-	-	0,47	0,066
3	1,22	1,81	1,00	1,00	0,20	-	-	-	-	-	0,85	0,120
4	1,22	1,81	1,00	1,00	0,20	-	-	-	-	-	0,85	0,120
5	6,07	9,00	4,98	4,98	1,00	-	-	-	-	-	4,23	0,596
6	-	-	-	-	-	-	-	-	-	-	-	0,000
7	-	-	-	-	-	-	-	-	-	-	-	0,000
8	-	-	-	-	-	-	-	-	-	-	-	0,000
9	-	-	-	-	-	-	-	-	-	-	-	0,000
10	-	-	-	-	-	-	-	-	-	-	-	0,000

Table D.4: $CO_{2equivalent}$ emissions



CO2equi emissions	1	2	3	4	5	6	7	8	9	10	wg	xg
1	1,00	1,01	1,00	0,99	6,93	-	-	-	-	-	1,47	0,241
2	0,99	1,00	0,99	0,98	6,89	-	-	-	-	-	1,46	0,239
3	1,00	1,01	1,00	0,99	6,95	-	-	-	-	-	1,47	0,241
4	1,01	1,02	1,01	1,00	7,00	-	-	-	-	-	1,49	0,243
5	0,14	0,15	0,14	0,14	1,00	-	-	-	-	-	0,21	0,035
6	-	-	-	-	-	-	-	-	-	-	-	0,000
7	-	-	-	-	-	-	-	-	-	-	-	0,000
8	-	-	-	-	-	-	-	-	-	-	-	0,000
9	-	-	-	-	-	-	-	-	-	-	-	0,000
10	-	-	-	-	-	-	-	-	-	-	-	0,000

Table D.5: NO_x emissions



Nox	1	2	3	4	5	6	7	8	9	10	wg	xg
1	1,00	1,00	1,00	1,00	5,99	-	-	-	-	-	1,43	0,240
2	1,00	1,00	1,00	1,00	5,99	-	-	-	-	-	1,43	0,240
3	1,00	1,00	1,00	1,00	5,99	-	-	-	-	-	1,43	0,240
4	1,00	1,00	1,00	1,00	6,00	-	-	-	-	-	1,43	0,240
5	0,17	0,17	0,17	0,17	1,00	-	-	-	-	-	0,24	0,040
6	-	-	-	-	-	-	-	-	-	-	-	0,000
7	-	-	-	-	-	-	-	-	-	-	-	0,000
8	-	-	-	-	-	-	-	-	-	-	-	0,000
9	-	-	-	-	-	-	-	-	-	-	-	0,000
10	-	-	-	-	-	-	-	-	-	-	-	0,000

Table D.6: Noise

Noise	1	2	3	4	5	6	7	8	9	10	wg	xg	
1	1,00	1,00	0,20	0,25	5,00	-	-	-	-	-	0,76	0,102	
2	1,00	1,00	0,20	0,25	5,00	-	-	-	-	-	0,76	0,102	
3	5,00	5,00	1,00	2,00	9,00	-	-	-	-	-	3,39	0,457	
4	4,00	4,00	0,50	1,00	8,00	-	-	-	-	-	2,30	0,309	
5	0,20	0,20	0,11	0,13	1,00	-	-	-	-	-	0,22	0,030	
6	-	-	-	-	-	-	-	-	-	-	-	0,000	
7	-	-	-	-	-	-	-	-	-	-	-	0,000	
8	-	-	-	-	-	-	-	-	-	-	-	0,000	CI/RI (xg)
9	-	-	-	-	-	-	-	-	-	-	-	0,000	0,041
10	-	-	-	-	-	-	-	-	-	-	-	0,000	OK

Table D.7: Impact during construction

Impact during construction	1	2	3	4	5	6	7	8	9	10	wg	xg	
1	1,00	1,00	0,14	0,25	0,14	-	-	-	-	-	0,35	0,047	
2	1,00	1,00	0,14	0,25	0,14	-	-	-	-	-	0,35	0,047	
3	7,00	7,00	1,00	4,00	1,00	-	-	-	-	-	2,87	0,386	
4	4,00	4,00	0,25	1,00	0,25	-	-	-	-	-	1,00	0,134	
5	7,00	7,00	1,00	4,00	1,00	-	-	-	-	-	2,87	0,386	
6	-	-	-	-	-	-	-	-	-	-	-	0,000	
7	-	-	-	-	-	-	-	-	-	-	-	0,000	
8	-	-	-	-	-	-	-	-	-	-	-	0,000	CI/RI (xg)
9	-	-	-	-	-	-	-	-	-	-	-	0,000	0,025
10	-	-	-	-	-	-	-	-	-	-	-	0,000	OK

Table D.8: Impact on ecosystem

Impact on ecosystem	1	2	3	4	5	6	7	8	9	10	wg	xg	
1	1,00	1,00	2,00	2,00	9,00	-	-	-	-	-	2,05	0,309	
2	1,00	1,00	2,00	2,00	9,00	-	-	-	-	-	2,05	0,309	
3	0,50	0,50	1,00	1,00	9,00	-	-	-	-	-	1,18	0,178	
4	0,50	0,50	1,00	1,00	9,00	-	-	-	-	-	1,18	0,178	
5	0,11	0,11	0,11	0,11	1,00	-	-	-	-	-	0,17	0,026	
6	-	-	-	-	-	-	-	-	-	-	-	0,000	
7	-	-	-	-	-	-	-	-	-	-	-	0,000	
8	-	-	-	-	-	-	-	-	-	-	-	0,000	CI/RI (xg)
9	-	-	-	-	-	-	-	-	-	-	-	0,000	0,017
10	-	-	-	-	-	-	-	-	-	-	-	0,000	OK

Table D.9: N° of local employees

N° of local employee	1	2	3	4	5	6	7	8	9	10	wg	xg
1	1,00	0,96	1,22	1,22	4,79	-	-	-	-	-	1,47	0,257
2	1,04	1,00	1,27	1,27	5,00	-	-	-	-	-	1,53	0,268
3	0,82	0,79	1,00	1,00	3,93	-	-	-	-	-	1,20	0,211
4	0,82	0,79	1,00	1,00	3,93	-	-	-	-	-	1,20	0,211
5	0,21	0,20	0,25	0,25	1,00	-	-	-	-	-	0,31	0,054
6	-	-	-	-	-	-	-	-	-	-	-	0,000
7	-	-	-	-	-	-	-	-	-	-	-	0,000
8	-	-	-	-	-	-	-	-	-	-	-	0,000
9	-	-	-	-	-	-	-	-	-	-	-	0,000
10	-	-	-	-	-	-	-	-	-	-	-	0,000

Table D.10: Impact on health

Impact on health	1	2	3	4	5	6	7	8	9	10	wg	xg	
1	1,00	1,00	0,33	0,20	8,00	-	-	-	-	-	0,88	0,117	
2	1,00	1,00	0,33	0,20	8,00	-	-	-	-	-	0,88	0,117	
3	3,00	3,00	1,00	0,33	8,00	-	-	-	-	-	1,89	0,251	
4	5,00	5,00	3,00	1,00	9,00	-	-	-	-	-	3,68	0,490	
5	0,13	0,13	0,13	0,11	1,00	-	-	-	-	-	0,19	0,025	
6	-	-	-	-	-	-	-	-	-	-	-	0,000	
7	-	-	-	-	-	-	-	-	-	-	-	0,000	
8	-	-	-	-	-	-	-	-	-	-	-	0,000	CI/RI (xg)
9	-	-	-	-	-	-	-	-	-	-	-	0,000	0,079
10	-	-	-	-	-	-	-	-	-	-	-	0,000	OK

Table D.11: Heat connections

Heat connections increase	1	2	3	4	5	6	7	8	9	10	wg	xg
1	1,00	1,00	1,00	0,13	1,00	-	-	-	-	-	0,66	0,083
2	1,00	1,00	1,00	0,13	1,00	-	-	-	-	-	0,66	0,083
3	1,00	1,00	1,00	0,13	1,00	-	-	-	-	-	0,66	0,083
4	8,00	8,00	8,00	1,00	8,00	-	-	-	-	-	5,28	0,667
5	1,00	1,00	1,00	0,13	1,00	-	-	-	-	-	0,66	0,083
6	-	-	-	-	-	-	-	-	-	-	-	0,000
7	-	-	-	-	-	-	-	-	-	-	-	0,000
8	-	-	-	-	-	-	-	-	-	-	-	0,000
9	-	-	-	-	-	-	-	-	-	-	-	0,000
10	-	-	-	-	-	-	-	-	-	-	-	0,000

List of acronyms

AGECC	Advisory Group on Energy and Climate Change
AHP	Analytic Hierarchy Process
APG	Associated Petroleum Gas
CAPEX	CAPital EXpenditures
CCGT	Combyned Cycle Gas Turbine
CDM	Clean Development Mechanism
CI	Consistency Index
CR	Consistency Ratio
DME	DiMethylEther
EIA	Energy Information Administration
EIA	Environmental Impact Assessment
ELECTRE	ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality)
ET	Emission Trading
GDP	Gross Domestic Product
GGFR	Global Gas Flaring Reduction partnership
GHG	Greenhouse Gas
GNI	Gross National Income
GOR	Gas to Oil Ratio
GOSP	Gas Oil Separation Plant
GPV	Global Priority Vector
GTL	Gas To Liquid
GTP	Gas To Power
GTW	Gas To Wire

HDI	Human Development Index
IRR	Internal Rate of Return
JI	Joint Implementation
LF	Load Factor
LHV	Lower Heating Value
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
Mtoe	Million of tons of oil equivalent
Mton	Million of tons
mtpa	million of tons per annum
NOAA	National Oceanic and Atmosferical Agency
NPV	Net Present Value
ODA	Official Development Assistance
OPEX	OPerating EXpenditures
PBT	Pay-Back Time
ppmvd	parts per million on dry volume basis
PSA	Pressure Swing Adsorption
PSCs	Product Sharing Contracts
RI	Random Index
SCGT	Simple Cycle Gas Turbine
SCOT	Shell Claus Off Treatment
TEG	TriEthylene Glycol
TG	TurboGas
toe	tons of oil equivalent
TPES	Total Primary Energy Supply
UEMOA	Union Économique et Monétaire Ouest-africaine
USD	United States Dollar

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