Environmental and Economic Water Management in Shale Gas Extraction.

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Supplementary Information

This document contains the supplementary material for the article «*Environmental and Economic Water Management in Shale Gas Extraction*». The document is organized as follows:

S.1. Comparison between thermal and membrane-based technologies for all the subcategories of impact using ReCiPe Midpoint (H)

S.2. Waste Water Management: Mathematical model Formulation.

- Nomenclature
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- Model Parameter: typical values
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S3. Case Study Data and Results

- Case Study Data
- Results for the maximum profit optimization
- Results for the minimum total LCIA (endpoint)
- Results for the minimum fresh water consumption

S.1. Comparison between thermal and membrane-based technologies for all the subcategories of impact using ReCiPe Midpoint (H)

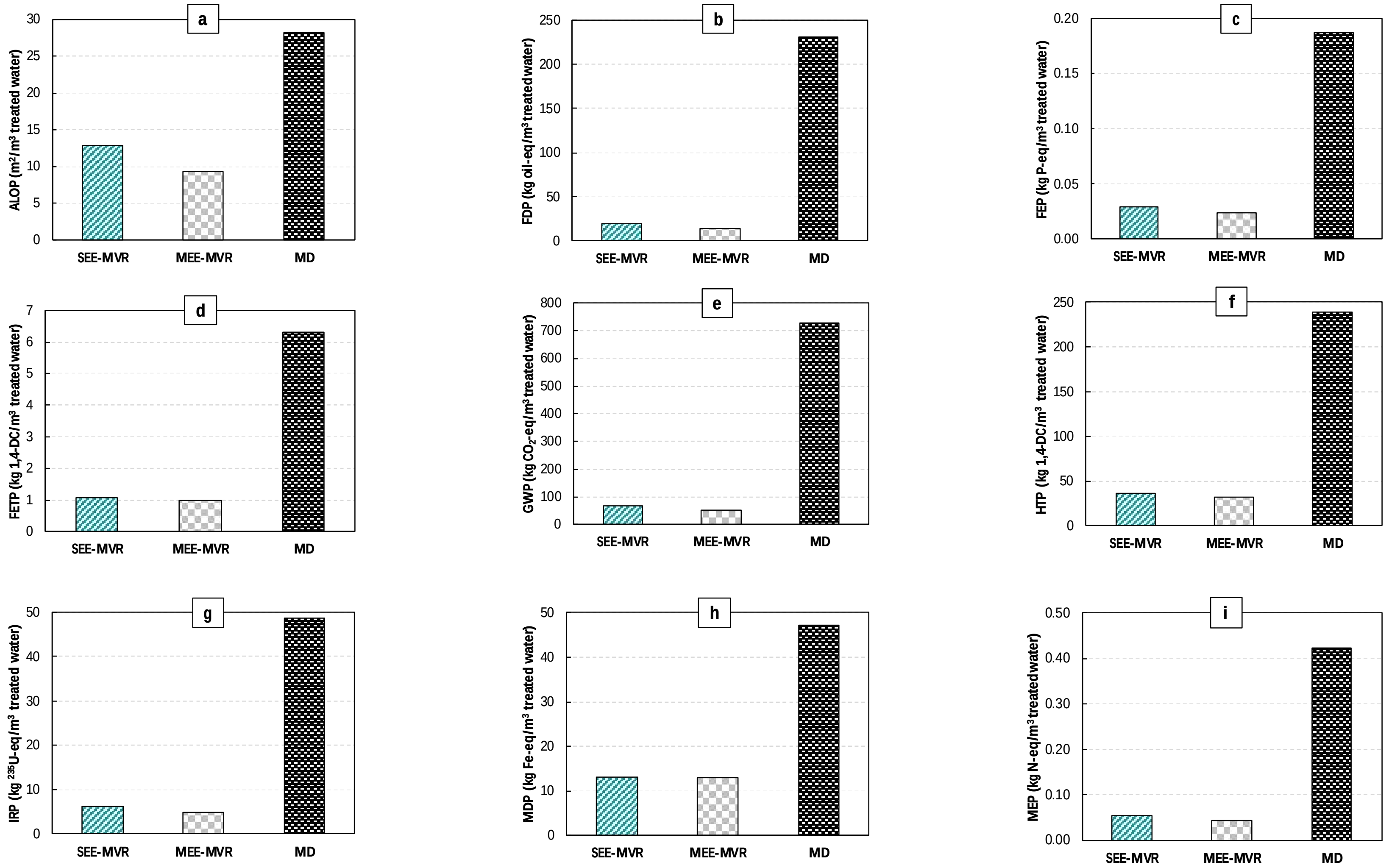

Figure S.1. Comparison between thermal and membrane-based technologies for all the subcategories of impact using ReCiPe Midpoint (H). a) Agricultural land occupation (ALOP), b) Fossil depletion (FDP), c) Freshwater eutrophication (FEP), d) Freshwater ecotoxicity (FETP), e) Global warming potential (GWP), f) Human toxicity (HTP), g) Ionizing radiation (IRP), h) Metal depletion (MDP), i) Marine eutrophication (MEP),

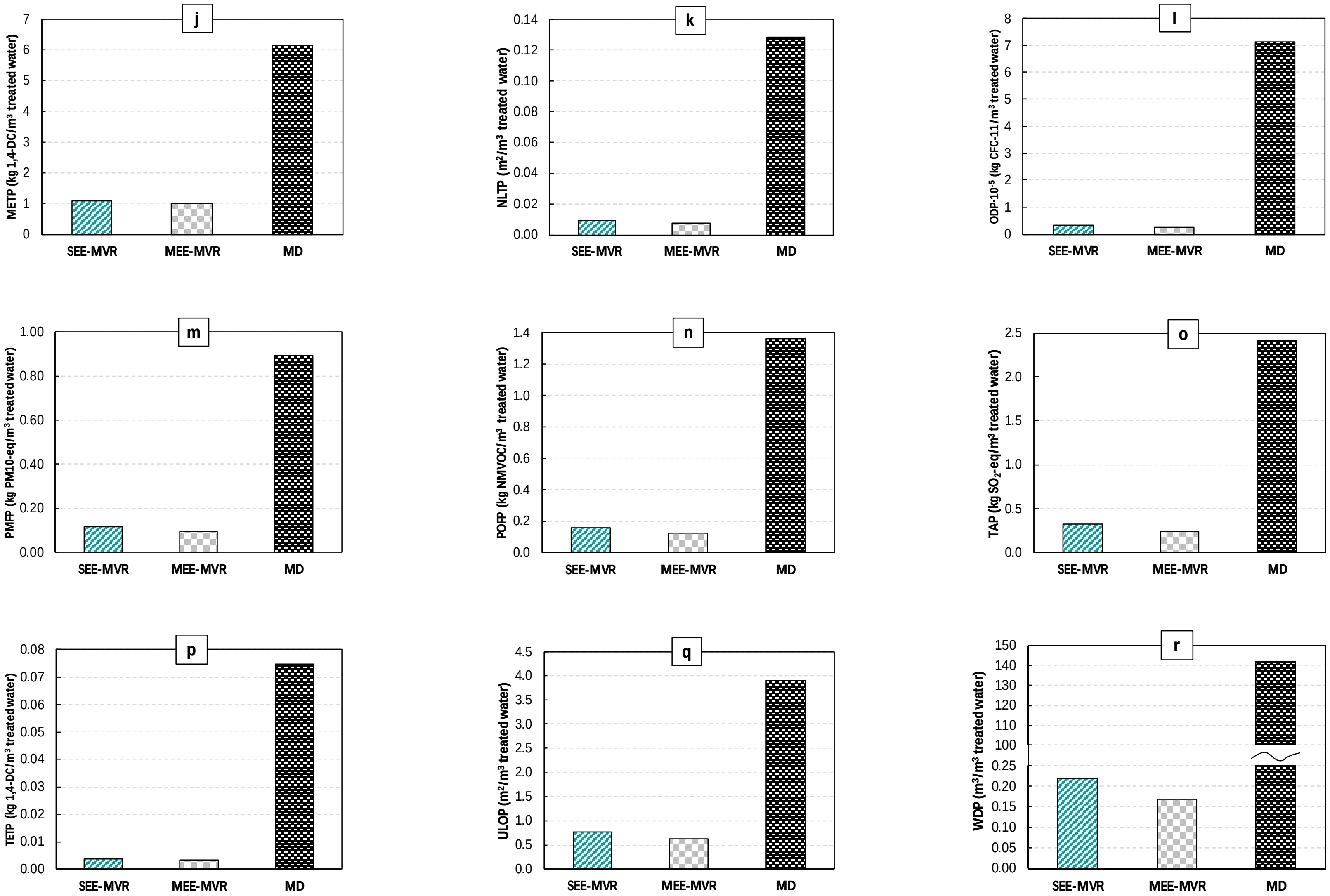

Figure S.1.(cont) Comparison between thermal and membrane-based technologies for all the subcategories of impact using ReCiPe Midpoint (H) j) Marine ecotoxicity (METP), k) Natural land transformation (NLTP), l) Ozone depletion (ODP), m) Particulate matter formation (PMFP), n) Photochemical oxidant formation (POFP), o) Terrestrial acidification (TAP), p) Terrestrial ecotoxicity (TETP), q) Urban land occupation (ULOP), and r) Water depletion (WDP).

S.2. Waste Water Management: Mathematical model Formulation

The shale gas water management mathematical model is based on the model proposed by Carrero-Parreño et al. [1] The equations that define this problem are detailed below:

NOMENCLATURE

Indexes

c	Fracturing crew
d	Disposal well
f	Source
k	Capacity
n	Onsite treatment
p	Wellpad
t	Time period
w	Well
wt	Treatment

Parameters

$D_{p,d}^{pad-dis}$	Distance from wellpad p to disposal well d
$D_{f,p}^{pad-source}$	Distance from source f to wellpad p
$D_{p}^{pad-off}$	Distance from wellpad p to offsite-treatment
$D_{p,pp}^{pad-pad}$	Distance from wellpad p to wellpad pp
$F_{t,p,w}^{well}$	Flowback water forecast for well w on wellpad p in time period t
$F_{n}^{on,LO}$	Minimum onsite capacity for treatment wt
$F_{n}^{on,UP}$	Maximum onsite capacity for treatment wt
$F_{k}^{cwt,UP}$	Maximum centralize water treatment capacity k
V_{s}^{UP}	Maximum storage volume of tank type s
WD_{w}	Water demand of well w
α_{k}^{cwt}	Cost coefficient of centralized water treatment k
α^{des}	Onsite treatment recovery factor
α_{d}^{dis}	Disposal coefficient cost coefficient for disposal d
α^{fr}	Friction reducer cost coefficient
α^{ft}	Fracturing tank cost coefficient
α^{fwt}	Fresh water tank cost coefficient
α_{p}^{on}	Onsite desalination cost coefficient on wellpad p
α^{pre}	Pretreatment recovery factor

α^{rec}	Centralized water treatment recovery factor
α^{reuse}	Pretreatment cost coefficient aiming its reuse
α_f^{source}	Freshwater cost coefficient in freshwater source *f*
α^{treat}	Pretreatment cost coefficient aiming its treatment
α^{truck}	Trucking cost coefficient
β^{ft}	Mobilize, demobilize and cleaning cost coefficient for storage tank
β_p^{on}	Maintenance cost coefficient for onsite treatment on wellpad *p*
τ_w	Time to fracture well *w*

Binary variables

$y_{t,p,w,c}^{hf}$	Indicates if well *w* on wellpad *p* is stimulating using fracturing crew *c* in time period *t*
$y_{t,p,n}^{on}$	Indicates if onsite treatment *n* is used on wellpad *p* in time period *t*

Variables

$f_{t,p,k}^{cwt,in}$	Inlet flow in centralized water treatment *k* in time period *t*
$f_{t,k}^{cwt,out}$	Outlet flow in centralized water treatment *k* in time period *t*
$f_{t,p}^{dem}$	Flowrate of water demand in wellpad *p* in time period *t*
$f_{t,p}^{fresh}$	Flowrate of freshwater used in hydraulic fracturing in wellpad *p* in time period *t*
$f_{t,p}^{imp}$	Flowrate of impaired water used in hydraulic fracturing in wellpad *p* in time period *t*
$f_{t,p,pp}^{imp,pad}$	Flowrate of impaired water from wellpad *p* to wellpad *pp* in time period *t*
$f_{t,p,d}^{on,brine}$	Brine flowrate after onsite desalination process in wellpad *p* in time period *t*
$f_{t,p}^{on,in}$	Onsite desalination inflow in wellpad *p* in time period *t*
$f_{t,p}^{on,out}$	Onsite desalination outflow in wellpad *p* in time period *t*
$f_{t,p}^{on,slud}$	Sludge flowrate after onsite desalination process in wellpad *p* in time period *t*
$f_{t,p}^{pad}$	Flowrate of produce water on wellpad *p* in time period *t*
$f_{t,p}^{pre,in}$	Onsite pretreatment inflow in wellpad *p* in time period *t*
$f_{t,p}^{pre,out}$	Onsite pretreatment outflow in wellpad *p* in time period *t*
$f_{t,p,f}^{source}$	Flowrate of freshwater from natural source *f* to wellpad *p* in time period *t*
$f_{t,p,w}^{well}$	Flowrate of produce water on well *w* wellpad *p* in time period *t*
$st_{t,p,s}$	Level of water in tank type *s* on wellpad *p* in time period *t*
$y_{t,p,w}^{fb}$	Indicates when the water starts to come out on well *w* on wellpad *p* in time period *t*

WASTE WATER MANAGEMENT MODEL.

Assignment constraint

Eq. (S1) guarantees that at the time period each well is going to fracture,

$$\sum_{t \in T} y_{t,p,w}^{hf} = 1 \qquad \forall w \in RPW_p, p \in P \tag{S1}$$

where $y_{t,p,w}^{hf}$ indicates that the well *w* in wellpad *p* is stimulating in time period *t*.

Eq. (S2) ensures that there is no overlap in drilling operations between different wells,

$$\sum_{w \in RPW_p} \sum_{tt=t-\tau_w+1}^{t} y_{tt,p,w}^{hf} = 1 \qquad \forall t \in T, p \in P \tag{S2}$$

where τ_w is a parameter that indicates the time required to fracture well *w*.

Shale water recovered

After fracturing a well, a portion of the freshwater injected returns to the wellhead,

$$y_{t,p,w}^{hf} = y_{t+\tau_w,p,w}^{fb} \qquad t \le T - \tau_w, \forall w \in RPW_p, p \in P \tag{S3}$$

where $y_{t,p,w}^{fb}$ represents the time period when the flowback water comes out. The binary variable $y_{t,p,w}^{fb}$ is treated as a continuous variable since its integrality is enforced by the Eq (S3)

The wastewater from each wellpad is calculated with **Eq. (S4)**,

$$f_{t,p,w}^{well} = \sum_{w \in RPW_p} \sum_{tt=0}^{tt \le t-1} F_{t-tt,p,w}^{well} \cdot y_{tt+1,p,w}^{fb} \qquad \forall t \in T, p \in P \tag{S4}$$

where $F_{t,p,w}^{well}$ are parameters that indicate flowback flowrate.

Eq. (S5) describes the mass balance of flowback water collected from the wells belonging to wellpad *p*,

$$f_{t,p}^{pad} = \sum_{w \in RPW_p} f_{t,p,w}^{well} \qquad \forall t \in T, p \in P \tag{S5}$$

Mass balance in storage tanks

The level of the fracturing tank in each time period ($st_{t-1,p,s}$) depends on water stored in the previous time period, the flowback water recovered after the hydraulic fracturing $\left(f_{t,p}^{pad} \right)$, the water sent to another wellpad to be reused ($f_{t,pp,p}^{imp,pad}$), the water sent to CWT ($f_{t,p,k}^{cwt,in}$) or onsite ($f_{t,p}^{onpre,in}$) treatment and the water sent to disposal ($f_{t,p,d}^{dis}$). The mass balance in the storage tank is described in **Eq. (S6).**

$$\begin{aligned} st_{t-1,p,s} + f_{t,p}^{pad} + \sum_{\substack{pp \in P \\ pp \neq p}} f_{t,pp,p}^{imp,pad} &= st_{t,p,s} + \sum_{\substack{pp \in P \\ pp \neq p}} f_{t,p,pp}^{imp,pad} \\ &+ f_{t,p}^{onpre,in} + \sum_{k \in K} f_{t,p,k}^{cwt,in} + \sum_{d \in D} f_{t,p,d}^{dis} \qquad \forall t \in T, p \in P, s \in \{s1\} \end{aligned} \tag{S6}$$

The fresh water is also stored in portable tanks. The mass balance is detailed in **Eq. (S7)**.

$$st_{t-1,p,s} + \sum_{f \in F} f_{t,p,f}^{source} = st_{t,p,s} + f_{t,p}^{fresh} \qquad \forall t \in T, p \in P, s \in \{s2\} \tag{S7}$$

The volume of the tank (v_s) is calculated by **Eq. (S8)**,

$$st_{t,p,s} + \theta_{t,p,s} \le v_s \qquad \forall t \in T, p \in P, s \in S \tag{S8}$$

where $\theta_{t,p,s}$ represents the inlet water in the storage tank divided by the number of days in a week. This variable is introduced due to as the time horizon is discretized into weeks, the storage tank should handle the inlet water that comes from one day.

The volume of the tank is bounded by the maximum storage capacity allowed in a wellpad per week.

$$v_s \le V_s^{UP} \qquad \forall s \in S \tag{S9}$$

Water demand

The water demand per wellpad ($f_{t,p}^{dem}$) can be provided by a mixture of impaired water ($f_{t,p}^{imp}$) or fresh ($f_{t,p}^{fresh}$),

$$f_{t,p}^{dem} = f_{t,p}^{fresh} + f_{t,p}^{imp} \qquad \forall t \in T, p \in P \tag{S10}$$

The amount of water demand per well is given by **Eq. (S11)**,

$$f_{t,p}^{dem} = \sum_{w \in RPW_p} f_{t,p,w}^{dem} \qquad \forall t \in T, p \in P \tag{S11}$$

Eq. (S12) indicates that the water when the well is going to be drilled, must be greater or equal than the well water demand (WD_w),

$$f_{t,p,w}^{dem} \geq WD_w \cdot \sum_{c \in C} y_{t,p,w,c}^{hf} \qquad \forall t \in T, w \in RPW_p, p \in P \tag{S12}$$

Onsite treatment

Onsite pretreatment mass balance is described in **Eq. (S13)**,

$$f_{t,p}^{pre,out} + f_{t,p}^{on,slud} = f_{t,p}^{pre,in} \qquad \forall t \in T, p \in P \tag{S13}$$

The recovery factor (α^{pre}) is used to model the relationship between the inlet and outlet streams.

$$f_{t,p}^{pre,out} = \alpha^{pre} \cdot f_{t,p}^{pre,in} \qquad \forall t \in T, p \in P \tag{S14}$$

The outlet pretreated water can be used as a fracturing fluid ($f_{t,p}^{imp}$) or/and can be sent to onsite desalination treatment ($f_{t,p}^{on,in}$),

$$f_{t,p}^{pre,out} = f_{t,p}^{imp} + f_{t,p}^{on,in} \qquad \forall t \in T, p \in P \tag{S15}$$

Mass balance around onsite desalination technology is given by **Eq. (S16)**,

$$f_{t,p}^{on,out} + f_{t,p}^{on,brine} = f_{t,p}^{on,in} \qquad \forall t \in T, p \in P \tag{S16}$$

Again, the relation between inlet and outlet mass flowrate in onsite desalination unit is addressed by using the recovery factor (α^{on}),

$$f_{t,p}^{on,out} = \alpha^{on} \cdot f_{t,p}^{on,in} \qquad \forall t \in T, p \in P \qquad \forall t \in T, p \in P \tag{S17}$$

The following equation **Eq. (S18)** represents the maximum and minimum capacity of the desalination treatment.

$$F^{on,LO} \cdot y_{t,p}^{on} \leq f_{t,p}^{on,in} \leq F^{on,UP} \cdot y_{t,p}^{on} \qquad \forall t \in T, p \in P \tag{S18}$$

Centralized water treatment

Eq. (S19) shows the connection between inlet and outlet streams, and **Eq. (S20)** limits the inlet water of CWT *k* with the maximum capacity allowed.

$$f_{t,k}^{cwt,out} = \alpha_k^{off} \cdot \sum_{p \in P} f_{t,p,k}^{cwt,in} \qquad \forall t \in T, k \in K \tag{S19}$$

$$\sum_{p \in P} f_{t,p,k}^{cwt,in} \le F_k^{cwt,UP} \qquad \forall t \in T, k \in K \tag{S20}$$

Objective function

Different objective functions have been considered depending on the case studied. We solve a multi-objective optimization problem considering two objective functions (**Eq. (S21)** and **Eq. (S22)**). Specifically, the gross profit to be maximized includes revenue from shale gas and expenses for wellpad construction and preparation, shale gas production and water-related costs. The life cycle impact assessment minimizes environmental impacts associated with water activities.

$$\begin{aligned}
\max: GP = & \sum_{t \in T} \sum_{p \in P} \sum_{w \in RPW_p} \sum_{tt=0}^{tt \le t-1} F_{t-tt,p,w}^{gas} \cdot y_{tt+1,p,w}^{fb} \cdot \alpha_t^{gas} \\
& - \sum_{t \in T} \sum_{p \in P} [\sum_{d \in D} \alpha_d^{dis} \cdot f_{t,p,d}^{dis} \\
& + \sum_{w \in RPW_p} (\alpha^{drill} \cdot y_{t,p,w}^{hf} + \alpha^{prod} \cdot f_{t,p,w}^{gas}) \\
& + \sum_{f \in F} \alpha_f^{source} \cdot f_{t,p,f}^{source} \\
& + \alpha^{fr} \cdot f_{t,p}^{imp} \\
& + \alpha^{reuse} \cdot f_{t,p}^{imp} + \alpha^{treat} \cdot f_{t,p}^{on,in} + \alpha_p^{on} \cdot f_{t,p}^{on,in} + \beta_p^{on} \cdot y_p^{on} \\
& + \sum_{k \in K} \alpha_k^{cwt} \cdot f_{t,p,k}^{cwt,in} \\
& + (\sum_{f \in F} f_{t,p,f}^{source} \cdot D_{f,p}^{pad-source} + \sum_{k \in K} f_{t,k}^{cwt,in} \cdot D_{p,k}^{pad-cwt} + \sum_{pp \in P} f_{t,p,pp}^{pad,imp} \cdot D_{p,pp}^{pad-pad}) \cdot \alpha_p^{trans}] \\
& + \alpha^{fwt} \cdot v_{fwt} + \alpha^{ft} \cdot v_{ft} + \beta^{ft}
\end{aligned} \tag{S21}$$

$$\begin{aligned}
\min: LCIA = & \sum_{t \in T} \sum_{p \in P} [\sum_{f \in F} \sigma^{source} \cdot f_{t,p,f}^{source} \\
& + \sigma^{on} \cdot f_{t,p}^{on,in} \\
& + \sum_{k \in K} \alpha_k^{cwt} \cdot f_{t,p,k}^{cwt,in} \\
& + (\sum_{f \in F} f_{t,p,f}^{source} \cdot D_{f,p}^{pad-source} + \sum_{k \in K} f_{t,k}^{cwt,in} \cdot D_{p,k}^{pad-cwt} + \sum_{pp \in P} f_{t,p,pp}^{pad,imp} \cdot D_{p,pp}^{pad-pad}) \cdot \sigma^{trans}]
\end{aligned} \tag{S22}$$

Model Parameters: typical values

All data related with the case study is shown in the section (S???). However, in this section we show typical values for costs and other relevant parameter and the relevant references.

Table S.1. Cost coefficients.

Parameter	Value	Unit	Ref
Disposal cost (α_d^{dis})	90 - 120	$\$/m^3$	[2]
Truck cost (α^{truck})	0.15	$\$/km/m^3$	[2]
Fracturing tank cost (α^{fl}; β^{fl})	4.37; 52390	$\$/ m^3$; $	*
Freshwater tank cost (α^{fwt})	0.59	$\$/ m^3$	*
Pretreatment cost (α^{reuse}, α^{treat})	0.8 - 2.0	$\$/m^3$	[3]
Desalination cost (α_p^{ondes})	10 - 25	$\$/m^3$	[4,5]
Demobilize, mobilize and clean out cost (β_p^{ondes})	650 - 850	$/week	*
Centralized water treatment (α_k^{cwt})	42 - 84	$\$/m^3$	[2]
Friction reducer cost (α^{fr})	0.18 - 0.30	$\$/m^3$	*
Freshwater withdrawal cost (α_f^{source})	1.76 - 3.50	$\$/m^3$	[6]

* Provided by a company

Table S.2. Model parameters.

Parameter	Value	Unit	Ref
V_s^{UP}	60,000	m^3	*
$F_{t,p,w}^{well}$	2,400 - 9,300	m^3 $week^{-1}$	[7]
$f^{on,UP}$	4,000	m^3 $week^{-1}$	*
$f_k^{cwt,UP}$	16,700	m^3 $week^{-1}$	*
WD_w	7,500 - 37,000	m^3 $week^{-1}$	[7]
τ_w	1 - 5	weeks	[7]

* Provided by a shale gas company

References

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SHALE GAS WATER MANAGEMENT

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         Institute of Chemical Process Engineering

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BEST GLOBAL ENVIRONMENTAL ALTERNATIVE

RESULTS FOR THE CASE STUDY IN THE PAPER:

«Environmental and Economic Water Management in Shale Gas Extraction»

CONTENTS

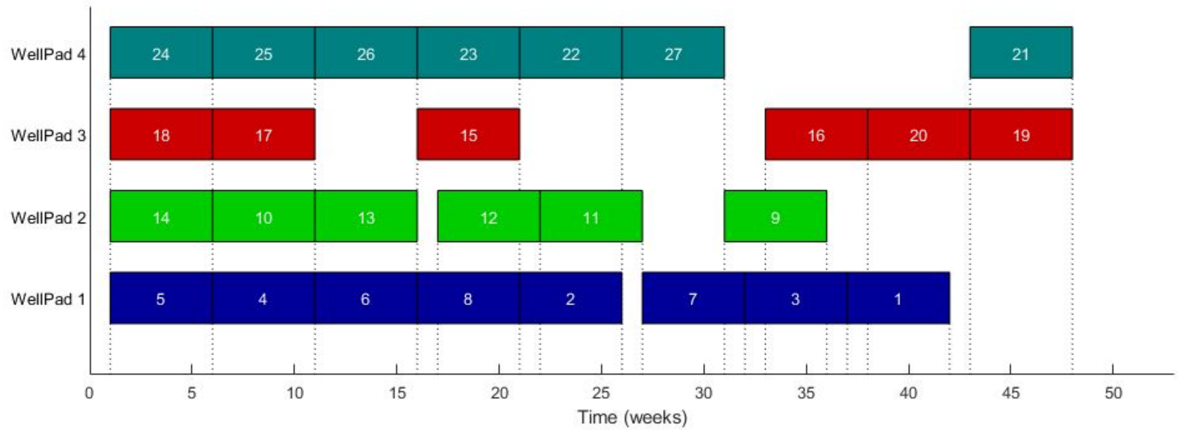
MODEL STATISTICS

```
Number of Variables                      :  11373.0
Numer of Discrete Variables              :   1165.0
Number of Equations                      :   9068.0
Number of non-zero elements              : 112950.0
Number of Iterations                     : 940439.0
CPU Generation Time (s)                  :   0.6090
CPU Solution Time (s)                    :  83.5310
Model Objective Value                    :   0.5189
```

RESULTS: SCHEDULING

The different wells must be schedule according to the following table.

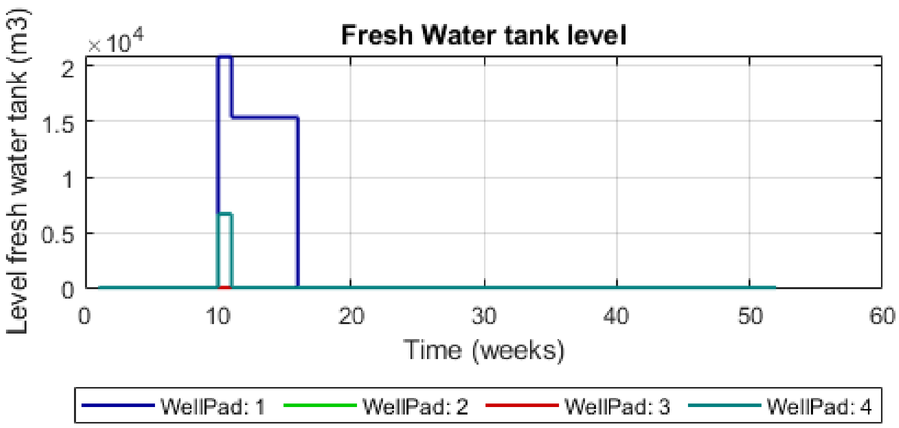
```
Well 1 in wellpad 1       Starts fracking at week   37     and ends fracking at week   42
Well 2 in wellpad 1       Starts fracking at week   21     and ends fracking at week   26
Well 3 in wellpad 1       Starts fracking at week   32     and ends fracking at week   37
Well 4 in wellpad 1       Starts fracking at week    6     and ends fracking at week   11
Well 5 in wellpad 1       Starts fracking at week    1     and ends fracking at week    6
Well 6 in wellpad 1       Starts fracking at week   11     and ends fracking at week   16
Well 7 in wellpad 1       Starts fracking at week   27     and ends fracking at week   32
Well 8 in wellpad 1       Starts fracking at week   16     and ends fracking at week   21
Well 9 in wellpad 2       Starts fracking at week   31     and ends fracking at week   36
Well 10 in wellpad 2      Starts fracking at week    6     and ends fracking at week   11
Well 11 in wellpad 2      Starts fracking at week   22     and ends fracking at week   27
Well 12 in wellpad 2      Starts fracking at week   17     and ends fracking at week   22
Well 13 in wellpad 2      Starts fracking at week   11     and ends fracking at week   16
Well 14 in wellpad 2      Starts fracking at week    1     and ends fracking at week    6
Well 15 in wellpad 3      Starts fracking at week   16     and ends fracking at week   21
Well 16 in wellpad 3      Starts fracking at week   33     and ends fracking at week   38
Well 17 in wellpad 3      Starts fracking at week    6     and ends fracking at week   11
Well 18 in wellpad 3      Starts fracking at week    1     and ends fracking at week    6
Well 19 in wellpad 3      Starts fracking at week   43     and ends fracking at week   48
Well 20 in wellpad 3      Starts fracking at week   38     and ends fracking at week   43
Well 21 in wellpad 4      Starts fracking at week   43     and ends fracking at week   48
Well 22 in wellpad 4      Starts fracking at week   21     and ends fracking at week   26
Well 23 in wellpad 4      Starts fracking at week   16     and ends fracking at week   21
Well 24 in wellpad 4      Starts fracking at week    1     and ends fracking at week    6
Well 25 in wellpad 4      Starts fracking at week    6     and ends fracking at week   11
Well 26 in wellpad 4      Starts fracking at week   11     and ends fracking at week   16
Well 27 in wellpad 4      Starts fracking at week   26     and ends fracking at week   31
```



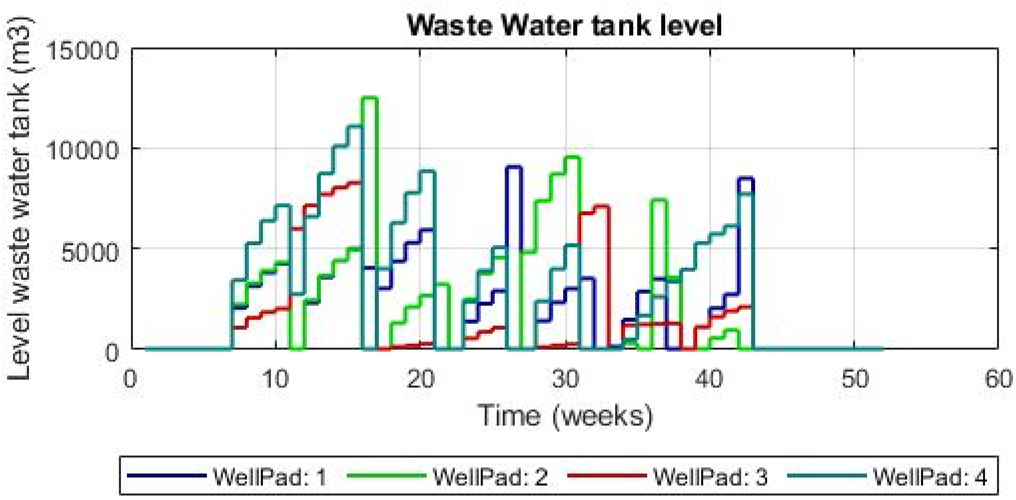
RESULTS: Storage Tanks. Volumes and Levels

```
Volume of fresh water tanks (m3)
    Well Pad   1 :    50000.0
    Well Pad   2 :    50000.0
    Well Pad   3 :    50000.0
    Well Pad   4 :    50000.0

Volume of waste water tanks (m3)
    Well Pad   1 :    50000.0
    Well Pad   2 :    50000.0
    Well Pad   3 :    50000.0
    Well Pad   4 :    50000.0
```

FRESH Water Tank Level



WASTE Water Tank Level



RESULTS: Main Flows

Total Flow from each water source to each WellPad (m3)

	WellPad 1	WellPad 2	WellPad 3	WellPad 4	Total
Source 1 :	20847.9	0.0	0.0	6655.2	27503.0
Source 2 :	0.0	0.0	0.0	0.0	0.0
Source 3 :	24907.5	35563.9	20275.2	31464.0	12210.6
Total :	45755.4	35563.9	20275.2	38119.2	

Total fresh water demand of each wellpad (m3)

WellPad 1 :	126000.0
WellPad 2 :	108000.0
WellPad 3 :	72000.0
WellPad 4 :	132000.0
Total :	438000.0

Total flowback water in each wellpad (m3)

WellPad 1 :	91634.5
WellPad 2 :	78614.5
WellPad 3 :	38240.0
WellPad 4 :	120850.0
Total :	329339.1

Total flowback recycled by each wellpad (m3)

WellPad 1 :	80244.6
WellPad 2 :	72436.1
WellPad 3 :	51724.8
WellPad 4 :	93880.8
Total :	298286.4

Total flow treated on-site in each wellpad(m3)

WellPad 1 :	4022.8
WellPad 2 :	1185.4
WellPad 3 :	8524.1
WellPad 4 :	7440.2
Total :	21172.5

Total flow sent to a C.W.T by each wellpad(m3)

WellPad 1 :	0.0
WellPad 2 :	0.0
WellPad 3 :	0.0
WellPad 4 :	0.0
Total :	0.0

Total flow sent to disposal by each wellpad(m3)

WellPad 1 :	0.0
WellPad 2 :	0.0
WellPad 3 :	0.0
WellPad 4 :	0.0
Total :	0.0

Total flow recycled between wellpads (m3)

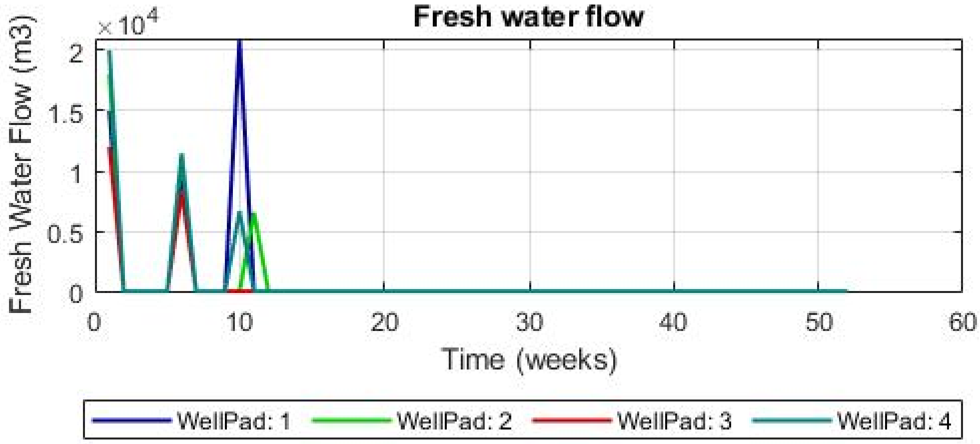
	WellPad 1	WellPad 2	WellPad 3	WellPad 4
WellPad 1 :	0.0	6014.3	15117.8	4087.2
WellPad 2 :	10032.5	0.0	5153.6	7407.1
WellPad 3 :	2424.7	1376.7	0.0	2919.8
WellPad 4 :	8001.2	12486.2	10322.1	0.0

RESULTS: Global data water utilization

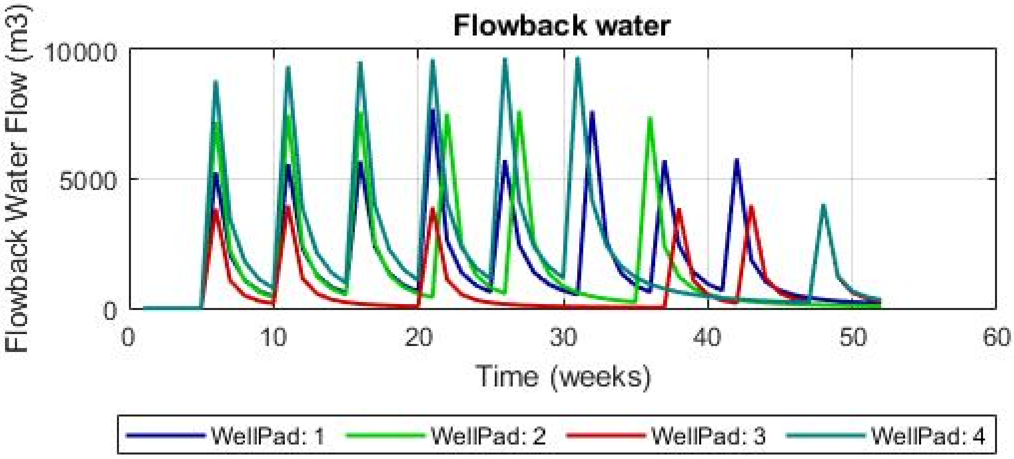
```
Total water demanded by WellPads (m3)  : 438000.0
Total fresh water consumption (m3)     : 139713.6
Total flowback water (m3)              : 329339.1
Total flowback water recycled (m3)     : 298286.4
Total sludge generated (m3)            :   9880.2
Total water desalinated on-site (m3)   :  21172.5
Total water desalinated off-site (m3)  :      0.0
Total water send to disposal (m3)      :      0.0

Percentage of fresh water saved (%)    :     68.1
```

RESULTS: Time dependent Water flow charts

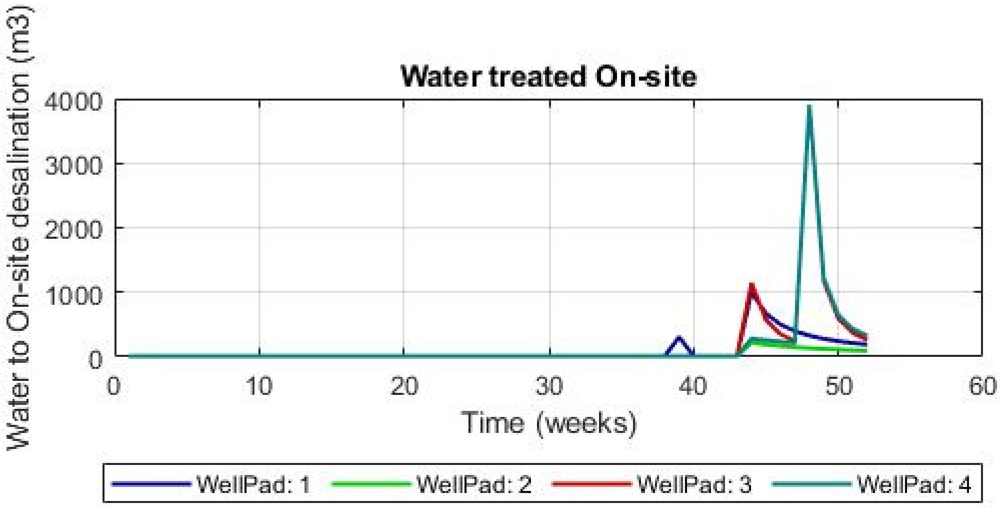
Total fresh water consumed in each wellpad



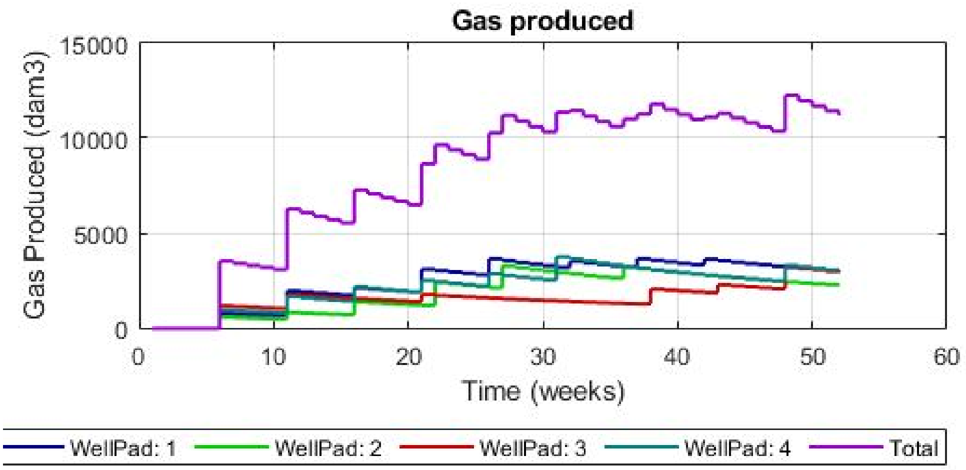
Total flowback water produced in each wellpad



Water to on-site desalination facility in each wellpad



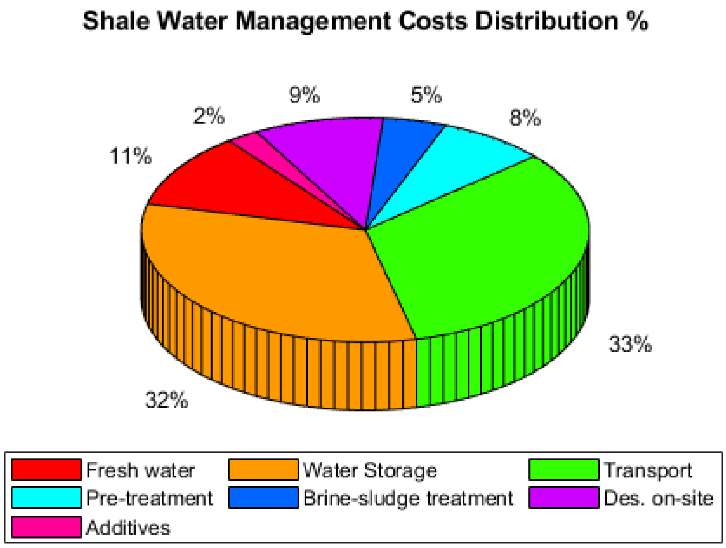
RESULTS : Gas Production Charts



RESULTS : Cost Distribution

Fresh water adquisition cost(k$)	:	402.5
Water transport cost(k$)	:	1213.1
Friction reducers cost(k$)	:	86.5
Fresh water storage cost (k$)	:	118.0
Waste water Storage cost(k$)	:	1083.6
Pre-treatment cost(k$)	:	288.3
On-site desalination cost(k$)	:	347.1
Off-site desalination cost(k$)	:	0.0
Water disposal cost(k$)	:	0.0
Brine and sludge disposal cost(k$)	:	169.4
Drilling costs(k$)	:	7290.0
Gas production cost(k$)	:	5961.2
Total Cost (k$)	:	16959.7
Total Gas Income (k$)	:	59017.6

Water related Cost Distribution Pie Chart (drilling and gas production are not included in the chart)



RESULTS : LCA

TOTAL ENVIRONMENTAL IMPACT

Environmental Impact (points/dam3·gas) : 0.51885

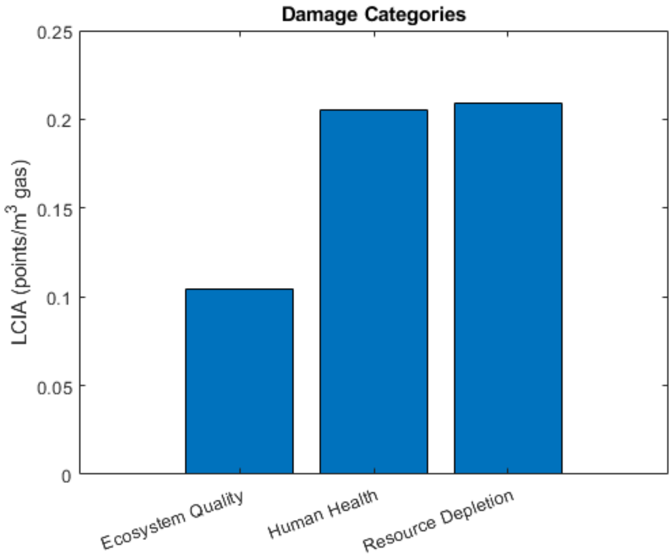
DAMAGE CATEGORIES

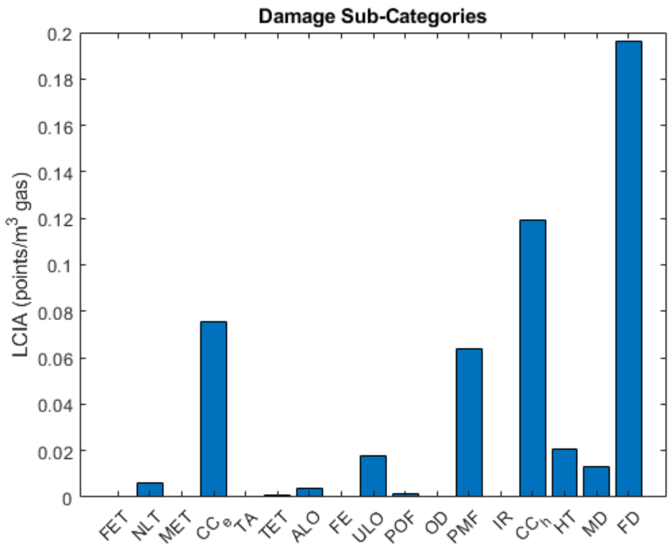
Ecosystem Quality (points/dam3·gas)	:	0.10462
Human Health (points/dam3·gas)	:	0.20497
Resources Depletion (points/dam3·gas)	:	0.20926

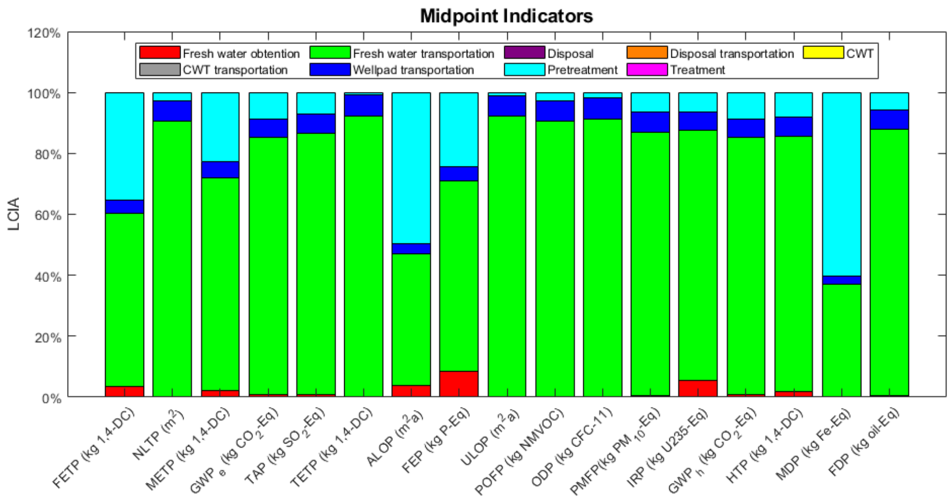
SUB-DAMAGE CATEGORIES

Freshwater Ecotoxicity	0.00003	points/dam3·gas	===>	0.02404	kg 1,4-DC
Natural Land Transformation	0.00616	points/dam3·gas	===>	0.00163	m2
Marine Ecotoxicity	0.00001	points/dam3·gas	===>	0.03797	kg 1,4-DC
Climate Change, Ecosystems	0.07545	points/dam3·gas	===>	1.66768	kg CO_2-Eq
Terrestrial Acidification	0.00029	points/dam3·gas	===>	0.02245	kg SO_2-Eq
Terrestrial Ecotoxicity	0.00084	points/dam3·gas	===>	0.00255	kg 1,4-DC
Agricultural Land Occupation	0.00393	points/dam3·gas	===>	0.10397	m2
Freshwater Eutrophication	0.00005	points/dam3·gas	===>	0.00043	kg P-Eq
Urban Land Occupation	0.01785	points/dam3·gas	===>	0.39002	m2
Photochem. Oxidant Formation	0.00129	points/dam3·gas	===>	0.03329	kg NMVOC
Ozone Depletion	0.00004	points/dam3·gas	===>	0.00000	kg CFC-11
Particulate Matter Formation	0.06368	points/dam3·gas	===>	0.01226	kg PM_10-Eq
Ionising Radiation	0.00012	points/dam3·gas	===>	0.35672	kg U235-Eq
Climate Change, Human Health	0.11938	points/dam3·gas	===>	2.63848	kg CO_2-Eq
Human Toxicity	0.02046	points/dam3·gas	===>	1.50817	kg 1,4-DC
Metal Depletion	0.01295	points/dam3·gas	===>	0.27896	kg Fe-Eq
Fossil Depletion	0.19632	points/dam3·gas	===>	1.63711	kg oil-Eq

FIGURES LCA







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SHALE GAS WATER MANAGEMENT

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Institute of Chemical Process Engineering

University of Alicante

LCA + Water Management Report

BEST ECONOMIC ALTERNATIVE

RESULTS FOR THE CASE STUDY IN THE PAPER:

«Environmental and Economic Water Management in Shale Gas Extraction»

CONTENTS

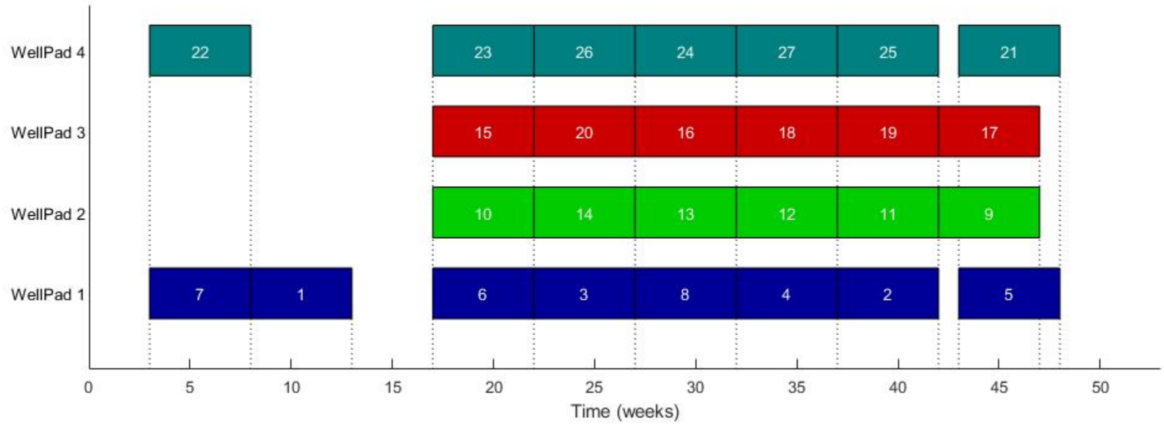
MODEL STATISTICS

Number of Variables	:	11373.0
Numer of Discrete Variables	:	1165.0
Number of Equations	:	9068.0
Number of non-zero elements	:	112950.0
Number of Iterations	:	25776.0
CPU Generation Time (s)	:	0.5940
CPU Solution Time (s)	:	3.9380
Model Objective Value	:	48643.1019

RESULTS: SCHEDULING

The different wells mus be schedule according to the following table.

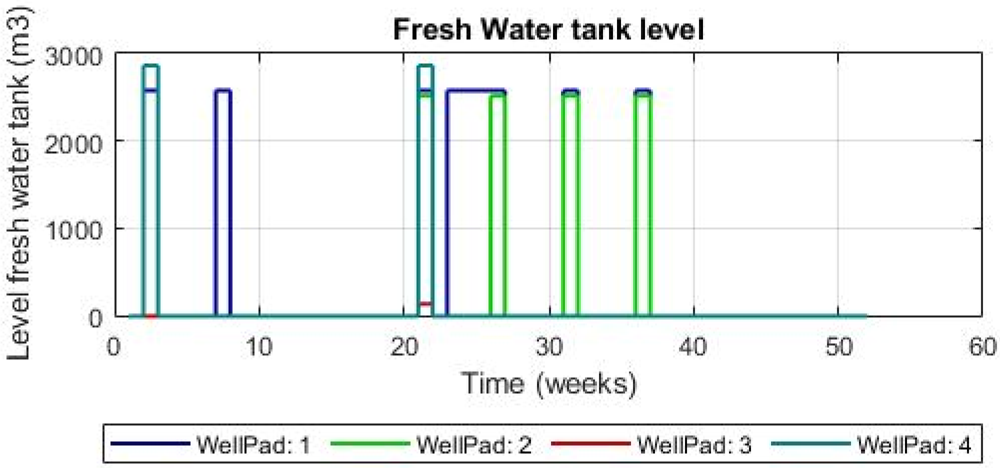
```
Well 1 in wellpad 1      Starts fracking at week    8     and ends fracking at week    13
Well 2 in wellpad 1      Starts fracking at week   37     and ends fracking at week    42
Well 3 in wellpad 1      Starts fracking at week   22     and ends fracking at week    27
Well 4 in wellpad 1      Starts fracking at week   32     and ends fracking at week    37
Well 5 in wellpad 1      Starts fracking at week   43     and ends fracking at week    48
Well 6 in wellpad 1      Starts fracking at week   17     and ends fracking at week    22
Well 7 in wellpad 1      Starts fracking at week    3     and ends fracking at week     8
Well 8 in wellpad 1      Starts fracking at week   27     and ends fracking at week    32
Well 9 in wellpad 2      Starts fracking at week   42     and ends fracking at week    47
Well 10 in wellpad 2     Starts fracking at week   17     and ends fracking at week    22
Well 11 in wellpad 2     Starts fracking at week   37     and ends fracking at week    42
Well 12 in wellpad 2     Starts fracking at week   32     and ends fracking at week    37
Well 13 in wellpad 2     Starts fracking at week   27     and ends fracking at week    32
Well 14 in wellpad 2     Starts fracking at week   22     and ends fracking at week    27
Well 15 in wellpad 3     Starts fracking at week   17     and ends fracking at week    22
Well 16 in wellpad 3     Starts fracking at week   27     and ends fracking at week    32
Well 17 in wellpad 3     Starts fracking at week   42     and ends fracking at week    47
Well 18 in wellpad 3     Starts fracking at week   32     and ends fracking at week    37
Well 19 in wellpad 3     Starts fracking at week   37     and ends fracking at week    42
Well 20 in wellpad 3     Starts fracking at week   22     and ends fracking at week    27
Well 21 in wellpad 4     Starts fracking at week   43     and ends fracking at week    48
Well 22 in wellpad 4     Starts fracking at week    3     and ends fracking at week     8
Well 23 in wellpad 4     Starts fracking at week   17     and ends fracking at week    22
Well 24 in wellpad 4     Starts fracking at week   27     and ends fracking at week    32
Well 25 in wellpad 4     Starts fracking at week   37     and ends fracking at week    42
Well 26 in wellpad 4     Starts fracking at week   22     and ends fracking at week    27
Well 27 in wellpad 4     Starts fracking at week   32     and ends fracking at week    37
```



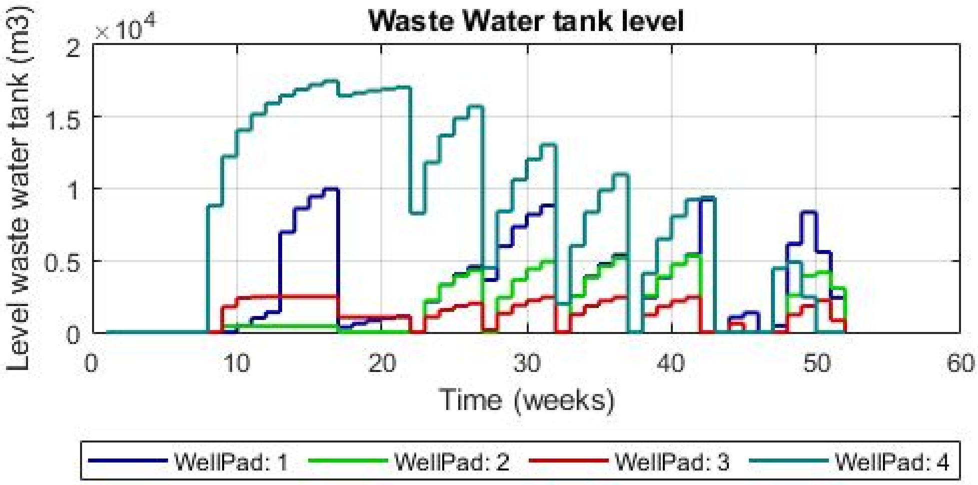
RESULTS: Storage Tanks. Volumes and Levels

```
Volume of fresh water tanks (m3)
    Well Pad   1 :     2571.4
    Well Pad   2 :     2511.8
    Well Pad   3 :      137.1
    Well Pad   4 :     2857.1

Volume of waste water tanks (m3)
    Well Pad   1 :    10036.1
    Well Pad   2 :     5392.8
    Well Pad   3 :     2481.8
    Well Pad   4 :    17529.7
```

FRESH Water Tank Level [stairs; regular charts]



WASTE Water Tank Level



RESULTS: Main Flows

Total Flow from each water source to each WellPad (m3)

	WellPad 1	WellPad 2	WellPad 3	WellPad 4	Total
Source 1 :	88714.6	0.0	1920.0	0.0	90634.6
Source 2 :	0.0	0.0	0.0	0.0	0.0
Source 3 :	0.0	46594.3	0.0	41665.0	88259.2
Total	88714.6	46594.3	1920.0	41665.0	

Total fresh water demand of each wellpad (m3)

WellPad 1 :	126000.0
WellPad 2 :	108000.0
WellPad 3 :	72000.0
WellPad 4 :	132000.0
Total :	438000.0

Total flowback water in each wellpad (m3)

WellPad 1 :	89122.9
WellPad 2 :	76235.8
WellPad 3 :	38232.4
WellPad 4 :	118500.7
Total :	322091.9

Total flowback recycled by each wellpad (m3)

WellPad 1 :	37285.4
WellPad 2 :	61405.7
WellPad 3 :	70080.0
WellPad 4 :	90335.0
Total :	259106.2

Total flow treated on-site in each wellpad(m3)

WellPad 1 :	16210.8
WellPad 2 :	0.0
WellPad 3 :	0.0
WellPad 4 :	37112.1
Total :	53322.9

Total flow sent to a C.W.T by each wellpad(m3)

WellPad 1 :	0.0
WellPad 2 :	0.0
WellPad 3 :	0.0
WellPad 4 :	0.0
Total :	0.0

Total flow sent to disposal by each wellpad(m3)

WellPad 1 :	0.0
WellPad 2 :	0.0
WellPad 3 :	0.0
WellPad 4 :	0.0
Total :	0.0

Total flow recycled between wellpads (m3)

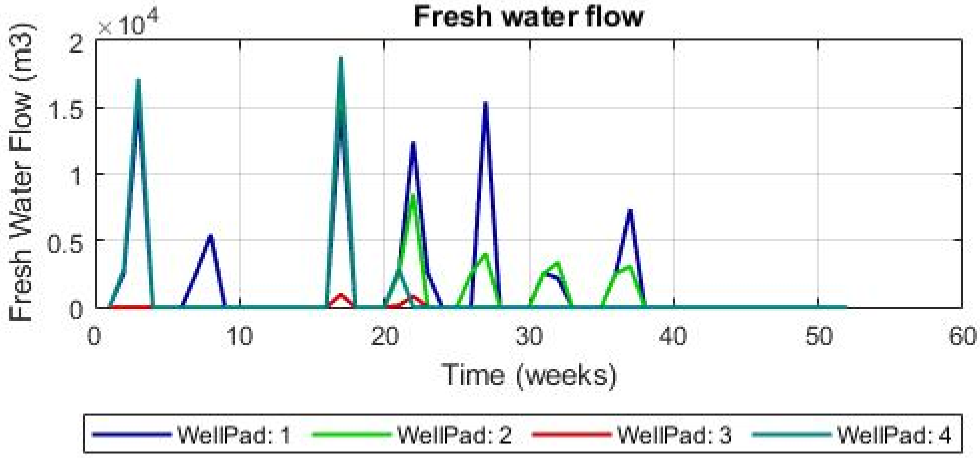
	WellPad 1	WellPad 2	WellPad 3	WellPad 4
WellPad 1 :	0.0	430.2	39315.5	3081.5
WellPad 2 :	2571.8	0.0	0.0	16393.3
WellPad 3 :	6283.3	0.0	0.0	2945.0
WellPad 4 :	0.0	5603.9	3927.7	0.0

RESULTS: Global data water utilization

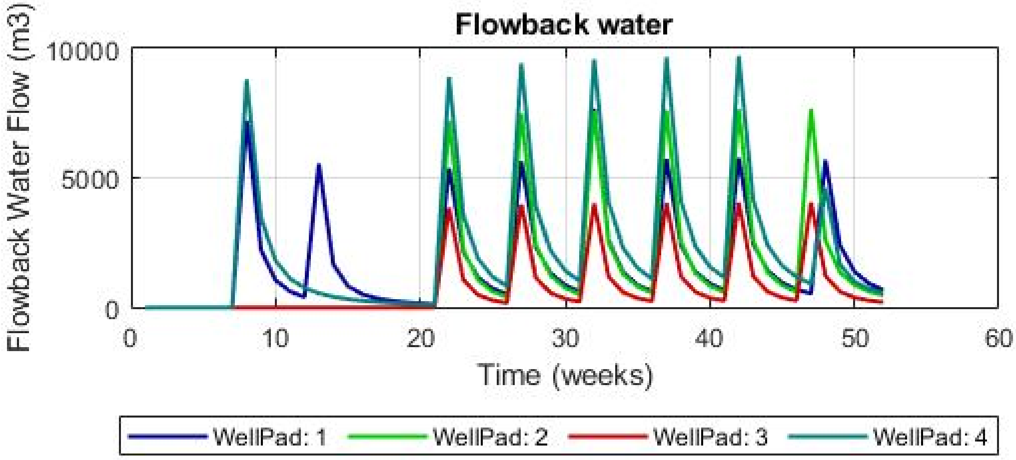
```
Total water demanded by WellPads (m3)  : 438000.0
Total fresh water consumption (m3)     : 178893.8
Total flowback water (m3)              : 322091.9
Total flowback water recycled (m3)     : 259106.2
Total sludge generated (m3)            :   9662.8
Total water desalinated on-site (m3)   :  53322.9
Total water desalinated off-site (m3)  :      0.0
Total water send to disposal (m3)      :      0.0

Percentage of fresh water saved (%)    :     59.2
```

RESULTS: Time dependent Water flow charts

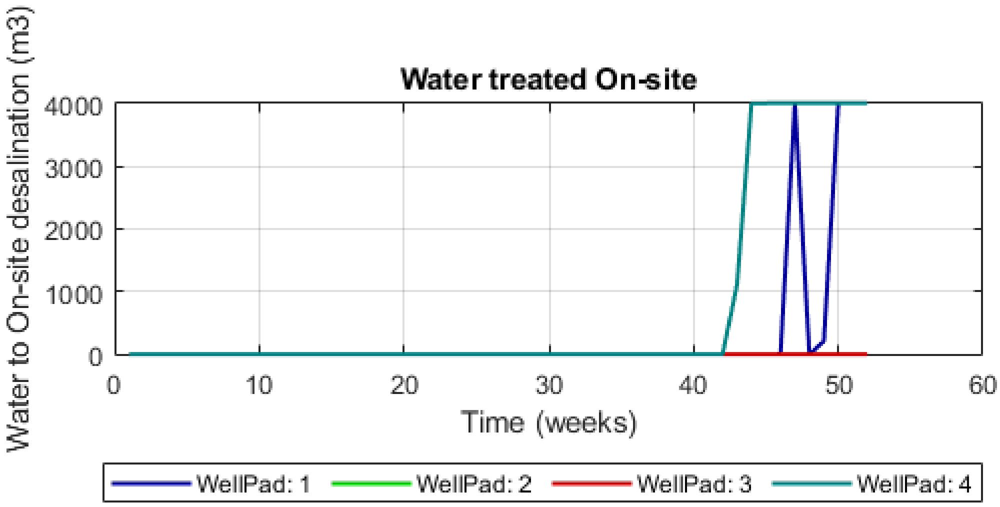
Total fresh water consumed in each wellpad



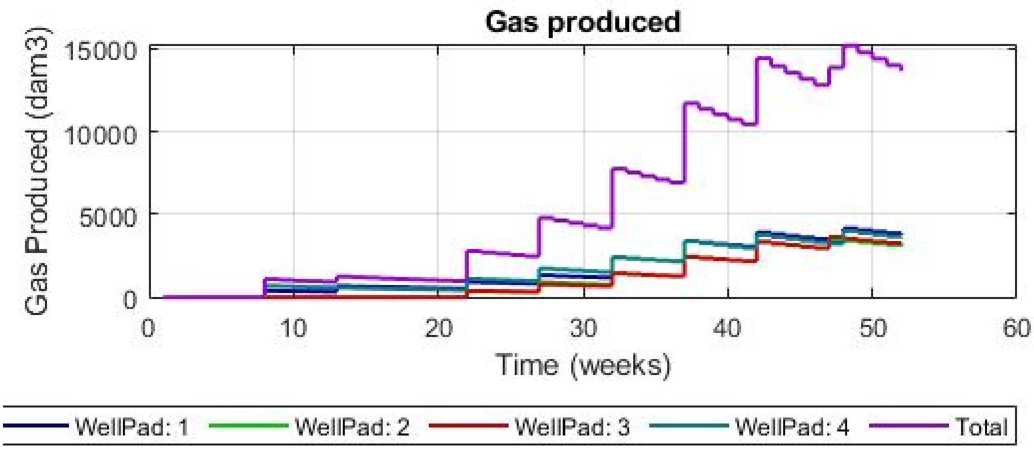
Total flowback water produced in each wellpad



Water to on-site desalination facility in each wellpad



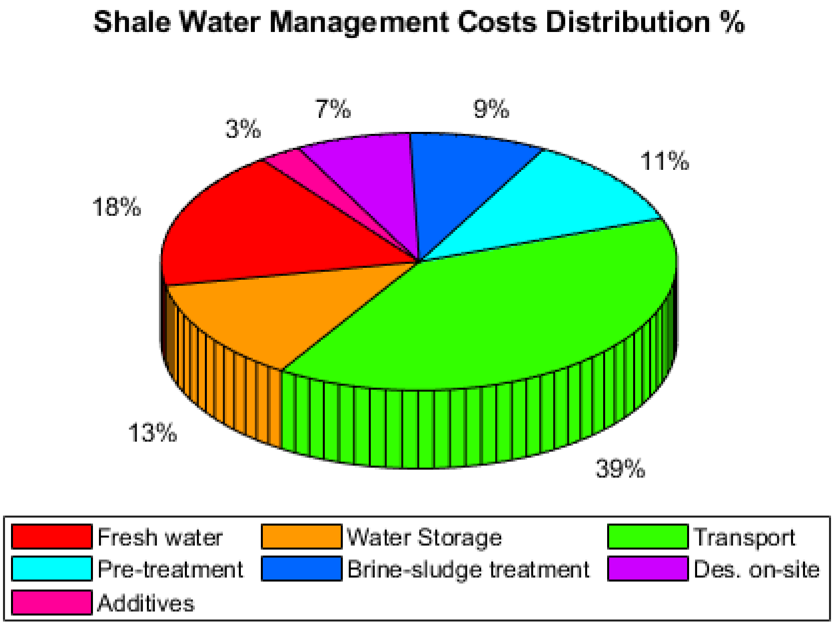
RESULTS : Gas Production Charts



RESULTS : Cost Distribution

```
Fresh water adquisition cost(k$)        :    498.8
Water transport cost(k$)                :   1117.8
Friction reducers cost(k$)              :     75.1
Fresh water storage cost (k$)           :      4.8
Waste water Storage cost(k$)            :    364.4
Pre-treatment cost(k$)                  :    325.6
On-site desalination cost(k$)           :    203.7
Off-site desalination cost(k$)          :      0.0
Water disposal cost(k$)                 :      0.0
Brine and sludge disposal cost(k$)      :    243.9
Drilling costs(k$)                      :   7290.0
Gas production cost(k$)                 :   4147.9

Total Cost (k$)                         :  14272.0

Total Gas Income (k$)                   :  62915.1
```

Water related Cost Distribution Pie Chart (drilling and gas production are not included in the chart)



RESULTS : LCA

TOTAL ENVIRONMENTAL IMPACT

Environmental Impact (points/dam3·gas) : 0.63906

DAMAGE CATEGORIES

Ecosystem Quality (points/dam3·gas) : 0.12884
Human Health (points/dam3·gas) : 0.25221
Resources Depletion (points/dam3·gas) : 0.25802

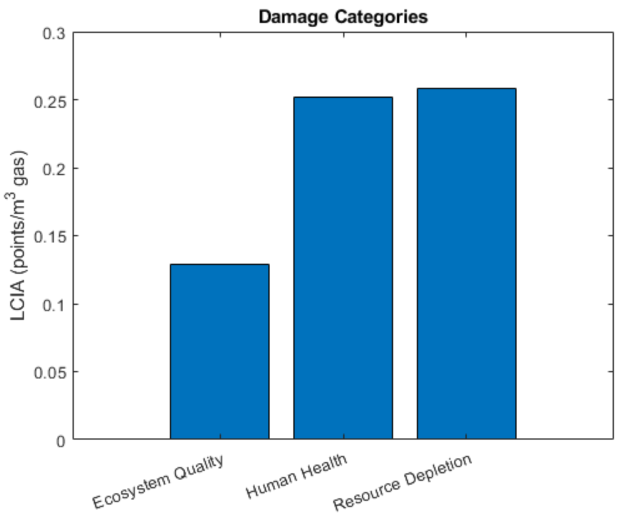
SUB-DAMAGE CATEGORIES

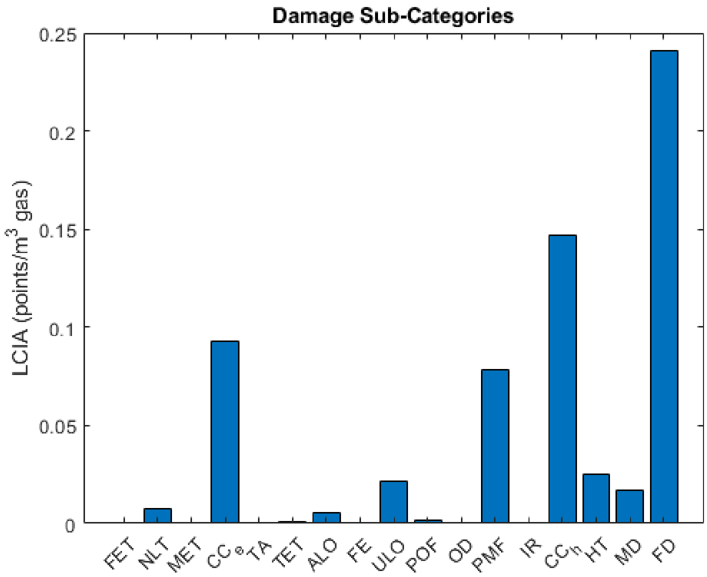
Freshwater Ecotoxicity	0.00004	points/dam3·gas	===>	0.03114	kg 1,4-DC
Natural Land Transformation	0.00749	points/dam3·gas	===>	0.00199	m2
Marine Ecotoxicity	0.00002	points/dam3·gas	===>	0.04805	kg 1,4-DC
Climate Change, Ecosystems	0.09297	points/dam3·gas	===>	2.05471	kg CO_2-Eq
Terrestrial Acidification	0.00035	points/dam3·gas	===>	0.02757	kg SO_2-Eq
Terrestrial Ecotoxicity	0.00102	points/dam3·gas	===>	0.00309	kg 1,4-DC
Agricultural Land Occupation	0.00522	points/dam3·gas	===>	0.13825	m2
Freshwater Eutrophication	0.00006	points/dam3·gas	===>	0.00055	kg P-Eq
Urban Land Occupation	0.02167	points/dam3·gas	===>	0.47347	m2

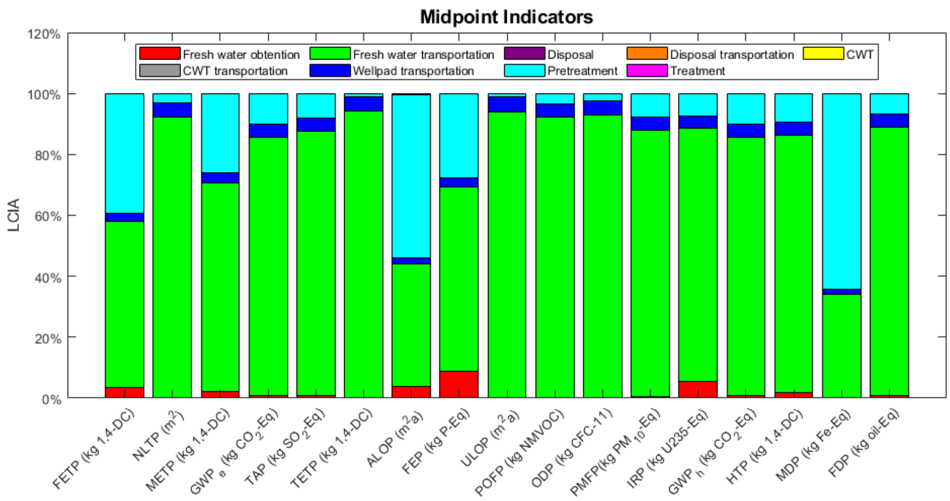
Photochem. Oxidant Formation	0.00160	points/dam3·gas	===>	0.04054	kg NMVOC
Ozone Depletion	0.00005	points/dam3·gas	===>	0.00000	kg CFC-11
Particulate Matter Formation	0.07813	points/dam3·gas	===>	0.01505	kg PM_10-Eq
Ionising Radiation	0.00014	points/dam3·gas	===>	0.43868	kg U235-Eq
Climate Change, Human Health	0.14708	points/dam3·gas	===>	3.25081	kg CO_2-Eq
Human Toxicity	0.02520	points/dam3·gas	===>	1.85754	kg 1,4-DC

Metal Depletion	0.01748	points/dam3·gas	===>	0.37656	kg Fe-Eq
Fossil Depletion	0.24054	points/dam3·gas	===>	2.00593	kg oil-Eq

FIGURES LCA







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SHALE GAS WATER MANAGEMENT

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MINIMUM FRESH WATER CONSUMPTION ALTERNATIVE

RESULTS FOR THE CASE STUDY IN THE PAPER:

«Environmental and Economic Water Management in Shale Gas Extraction»

CONTENTS

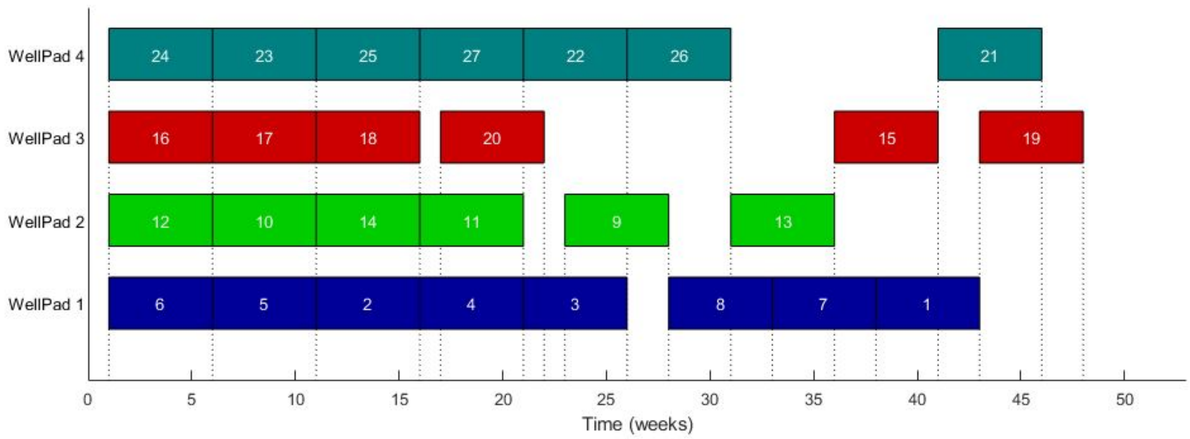
MODEL STATISTICS

```
Number of Variables                     :  11373.0
Numer of Discrete Variables             :   1165.0
Number of Equations                     :   9068.0
Number of non-zero elements             : 112950.0
Number of Iterations                    : 991149.0
CPU Generation Time (s)                 :   0.5940
CPU Solution Time (s)                   : 122.5790
Model Objective Value                   : 138897.1536
```

RESULTS: SCHEDULING

The different wells must be schedule according to the following table.

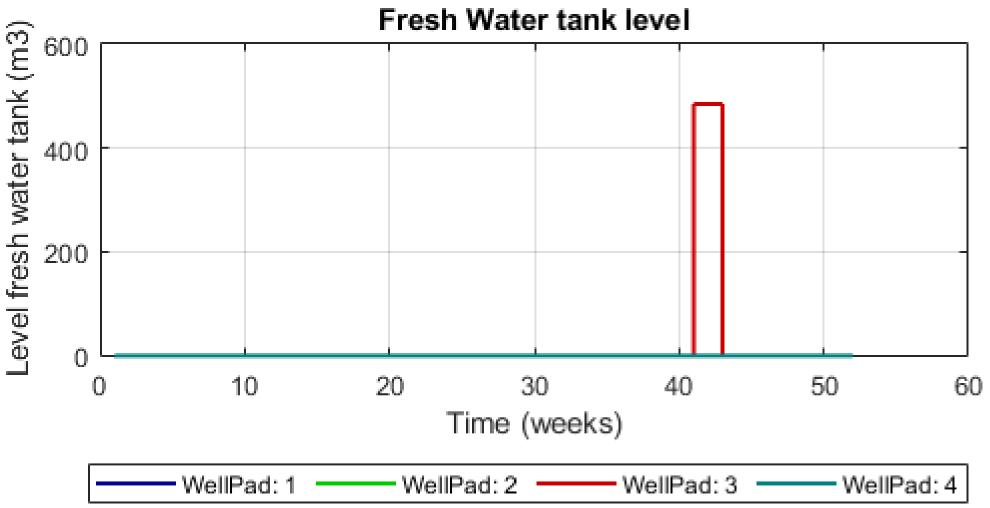
```
Well 1 in wellpad 1       Starts fracking at week   38     and ends fracking at week   43
Well 2 in wellpad 1       Starts fracking at week   11     and ends fracking at week   16
Well 3 in wellpad 1       Starts fracking at week   21     and ends fracking at week   26
Well 4 in wellpad 1       Starts fracking at week   16     and ends fracking at week   21
Well 5 in wellpad 1       Starts fracking at week    6     and ends fracking at week   11
Well 6 in wellpad 1       Starts fracking at week    1     and ends fracking at week    6
Well 7 in wellpad 1       Starts fracking at week   33     and ends fracking at week   38
Well 8 in wellpad 1       Starts fracking at week   28     and ends fracking at week   33
Well 9 in wellpad 2       Starts fracking at week   23     and ends fracking at week   28
Well 10 in wellpad 2      Starts fracking at week    6     and ends fracking at week   11
Well 11 in wellpad 2      Starts fracking at week   16     and ends fracking at week   21
Well 12 in wellpad 2      Starts fracking at week    1     and ends fracking at week    6
Well 13 in wellpad 2      Starts fracking at week   31     and ends fracking at week   36
Well 14 in wellpad 2      Starts fracking at week   11     and ends fracking at week   16
Well 15 in wellpad 3      Starts fracking at week   36     and ends fracking at week   41
Well 16 in wellpad 3      Starts fracking at week    1     and ends fracking at week    6
Well 17 in wellpad 3      Starts fracking at week    6     and ends fracking at week   11
Well 18 in wellpad 3      Starts fracking at week   11     and ends fracking at week   16
Well 19 in wellpad 3      Starts fracking at week   43     and ends fracking at week   48
Well 20 in wellpad 3      Starts fracking at week   17     and ends fracking at week   22
Well 21 in wellpad 4      Starts fracking at week   41     and ends fracking at week   46
Well 22 in wellpad 4      Starts fracking at week   21     and ends fracking at week   26
Well 23 in wellpad 4      Starts fracking at week    6     and ends fracking at week   11
Well 24 in wellpad 4      Starts fracking at week    1     and ends fracking at week    6
Well 25 in wellpad 4      Starts fracking at week   11     and ends fracking at week   16
Well 26 in wellpad 4      Starts fracking at week   26     and ends fracking at week   31
Well 27 in wellpad 4      Starts fracking at week   16     and ends fracking at week   21
```



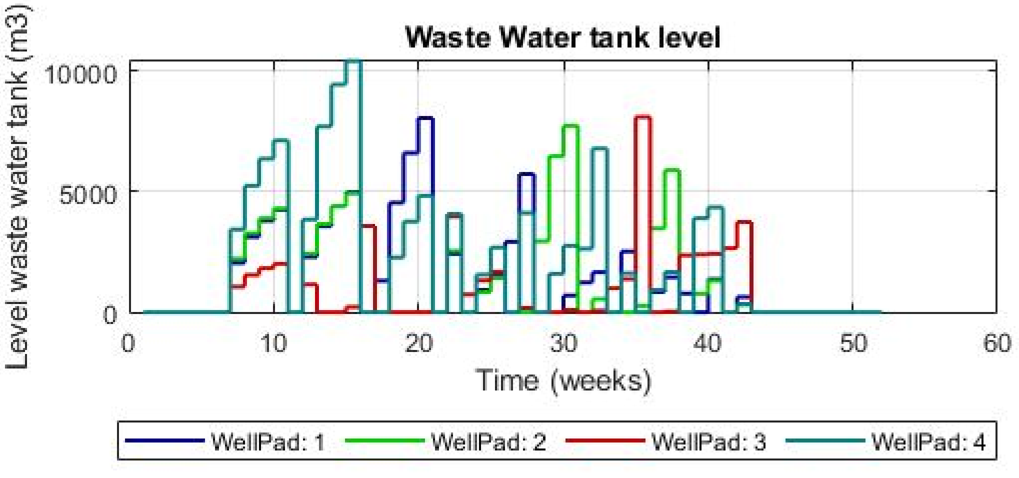
RESULTS: Storage Tanks. Volumes and Levels

```
Volume of fresh water tanks (m3)
    Well Pad   1 :    50000.0
    Well Pad   2 :    50000.0
    Well Pad   3 :    50000.0
    Well Pad   4 :    50000.0

Volume of waste water tanks (m3)
    Well Pad   1 :    50000.0
    Well Pad   2 :    50000.0
    Well Pad   3 :    50000.0
    Well Pad   4 :    50000.0
```

FRESH Water Tank Level



WASTE Water Tank Level



RESULTS: Main Flows

Total Flow from each water source to each WellPad (m3)

	WellPad 1	WellPad 2	WellPad 3	WellPad 4	Total
Source 1 :	0.0	0.0	483.0	0.0	483.0
Source 2 :	0.0	0.0	0.0	0.0	0.0
Source 3 :	24907.5	39559.4	31930.0	42017.2	138414.1
Total	24907.5	39559.4	32413.0	42017.2	

Total fresh water demand of each wellpad (m3)

WellPad 1 :	126000.0
WellPad 2 :	108000.0
WellPad 3 :	72000.0
WellPad 4 :	132000.0
Total :	438000.0

Total flowback water in each wellpad (m3)

WellPad 1 :	91596.1
WellPad 2 :	78609.0
WellPad 3 :	38483.7
WellPad 4 :	121070.7
Total :	329759.5

Total flowback recycled by each wellpad (m3)

WellPad 1 :	101092.5
WellPad 2 :	68440.6
WellPad 3 :	39587.0
WellPad 4 :	89982.8
Total :	299102.9

Total flow treated on-site in each wellpad(m3)

WellPad 1 :	5184.4
WellPad 2 :	1196.6
WellPad 3 :	6728.6
WellPad 4 :	7654.3
Total :	20763.8

Total flow sent to a C.W.T by each wellpad(m3)

WellPad 1 :	0.0
WellPad 2 :	0.0
WellPad 3 :	0.0
WellPad 4 :	0.0
Total :	0.0

Total flow sent to disposal by each wellpad(m3)

WellPad 1 :	0.0
WellPad 2 :	0.0
WellPad 3 :	0.0
WellPad 4 :	0.0
Total :	0.0

Total flow recycled between wellpads (m3)

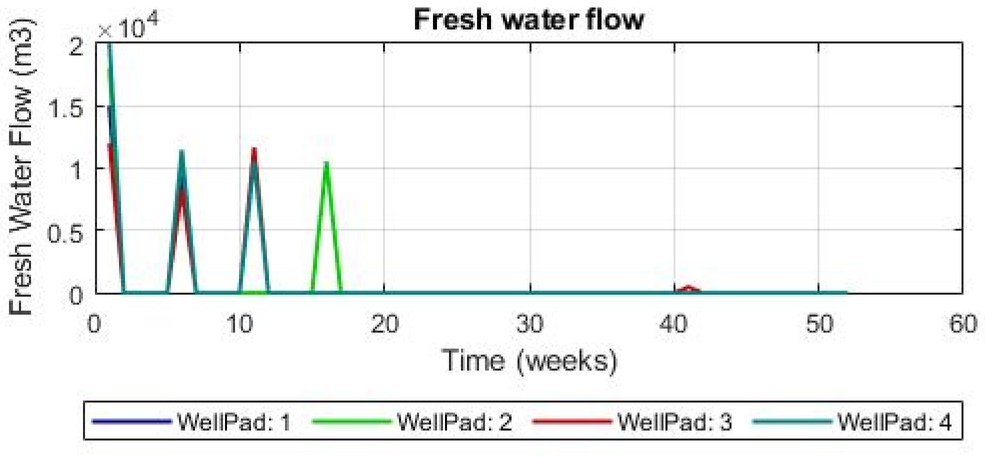
	WellPad 1	WellPad 2	WellPad 3	WellPad 4
WellPad 1 :	0.0	4790.5	11290.4	10081.5
WellPad 2 :	17129.2	0.0	11789.7	10417.0
WellPad 3 :	12132.2	4711.8	0.0	7635.4
WellPad 4 :	14868.6	23015.4	10663.7	0.0

RESULTS: Global data water utilization

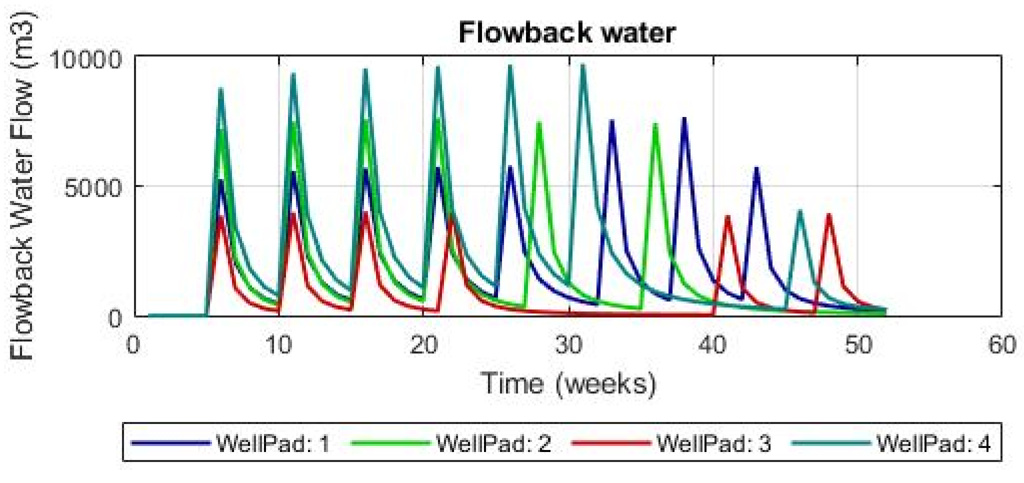
```
Total water demanded by WellPads (m3)  : 438000.0
Total fresh water consumption (m3)     : 138897.1
Total flowback water (m3)              : 329759.5
Total flowback water recycled (m3)     : 299102.9
Total sludge generated (m3)            :   9892.8
Total water desalinated on-site (m3)   :  20763.8
Total water desalinated off-site (m3)  :      0.0
Total water send to disposal (m3)      :      0.0

Percentage of fresh water saved (%)    :     68.3
```

RESULTS: Time dependent Water flow charts

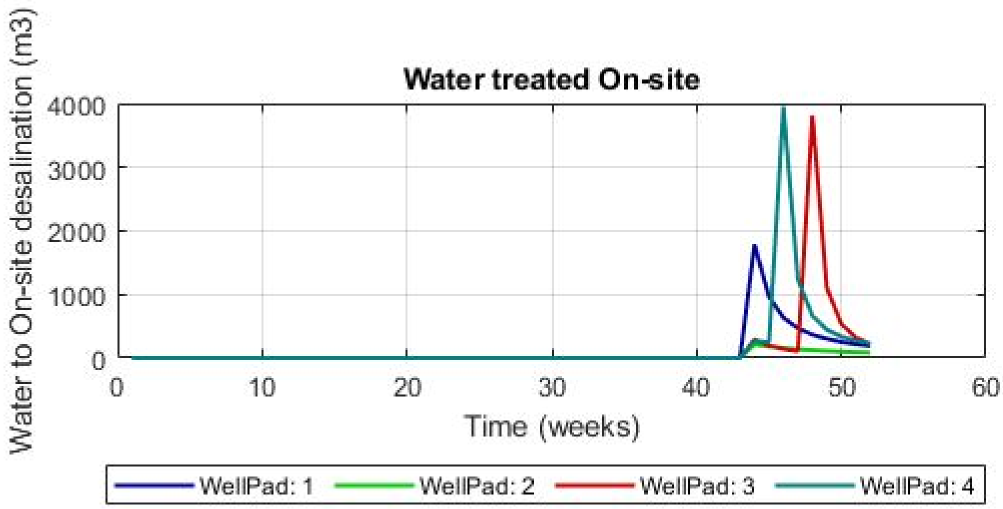
Total fresh water consumed in each wellpad



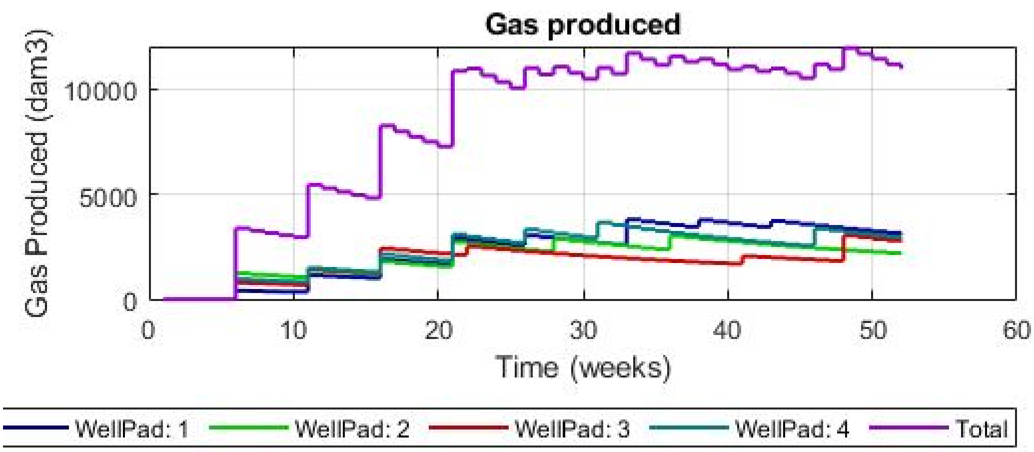
Total flowback water produced in each wellpad



Water to on-site desalination facility in each wellpad



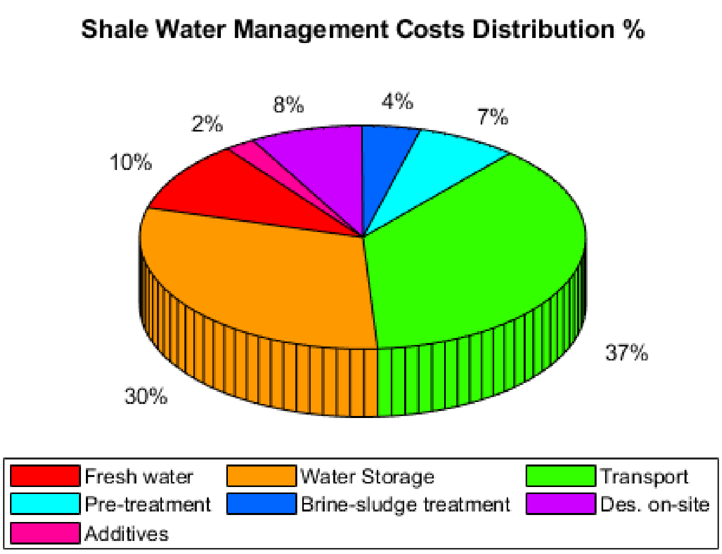
RESULTS : Gas Production Charts



RESULTS : Cost Distribution

Fresh water adquisition cost(k$)	:	408.2
Water transport cost(k$)	:	1483.8
Friction reducers cost(k$)	:	86.7
Fresh water storage cost (k$)	:	118.0
Waste water Storage cost(k$)	:	1083.6
Pre-treatment cost(k$)	:	288.1
On-site desalination cost(k$)	:	323.0
Off-site desalination cost(k$)	:	0.0
Water disposal cost(k$)	:	0.0
Brine and sludge disposal cost(k$)	:	168.5
Drilling costs(k$)	:	7290.0
Gas production cost(k$)	:	6050.9
Total Cost (k$)	:	17300.9
Total Gas Income (k$)	:	58593.7

Water related Cost Distribution Pie Chart (drilling and gas production are not included in the chart)



RESULTS : LCA

TOTAL ENVIRONMENTAL IMPACT

Environmental Impact (points/dam3·gas)	:	0.54656

DAMAGE CATEGORIES

Ecosystem Quality (points/dam3·gas)	:	0.11022
Human Health (points/dam3·gas)	:	0.21597
Resources Depletion (points/dam3·gas)	:	0.22037

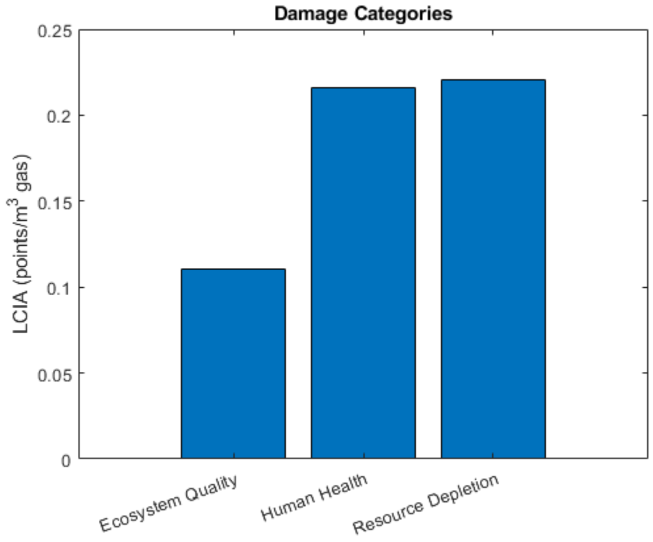
SUB-DAMAGE CATEGORIES

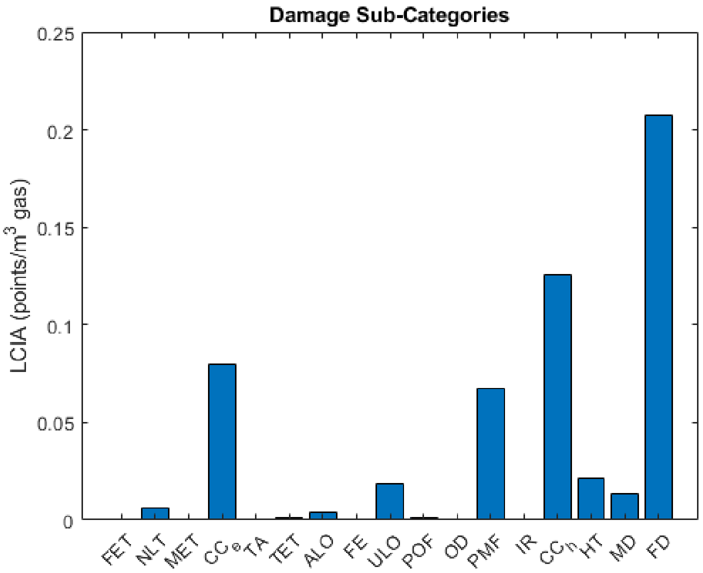
Freshwater Ecotoxicity	0.00003 points/dam3·gas	===>	0.02487	kg 1,4-DC
Natural Land Transformation	0.00652 points/dam3·gas	===>	0.00173	m2
Marine Ecotoxicity	0.00001 points/dam3·gas	===>	0.03962	kg 1,4-DC
Climate Change, Ecosystems	0.07947 points/dam3·gas	===>	1.75645	kg CO_2-Eq
Terrestrial Acidification	0.00030 points/dam3·gas	===>	0.02367	kg SO_2-Eq
Terrestrial Ecotoxicity	0.00089 points/dam3·gas	===>	0.00270	kg 1,4-DC
Agricultural Land Occupation	0.00404 points/dam3·gas	===>	0.10654	m2
Freshwater Eutrophication	0.00005 points/dam3·gas	===>	0.00044	kg P-Eq
Urban Land Occupation	0.01890 points/dam3·gas	===>	0.41288	m2

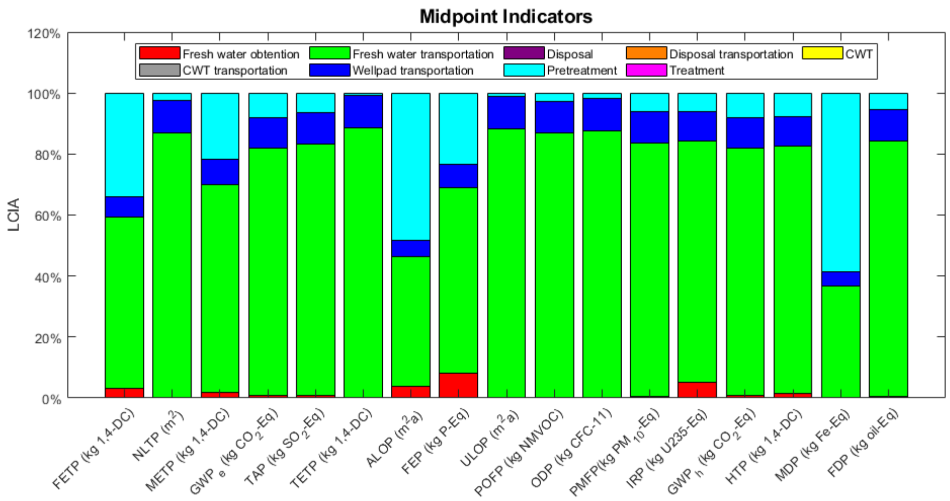
Photochem. Oxidant Formation	0.00136 points/dam3·gas	===>	0.03520	kg NMVOC
Ozone Depletion	0.00004 points/dam3·gas	===>	0.00000	kg CFC-11
Particulate Matter Formation	0.06716 points/dam3·gas	===>	0.01293	kg PM_10-Eq
Ionising Radiation	0.00012 points/dam3·gas	===>	0.37521	kg U235-Eq
Climate Change, Human Health	0.12573 points/dam3·gas	===>	2.77893	kg CO_2-Eq
Human Toxicity	0.02155 points/dam3·gas	===>	1.58815	kg 1,4-DC

Metal Depletion	0.01321 points/dam3·gas	===>	0.28467	kg Fe-Eq
Fossil Depletion	0.20716 points/dam3·gas	===>	1.72753	kg oil-Eq

FIGURES LCA







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