



# **UPGRADED CALCULATOR FOR CO<sub>2</sub> PIPELINE SYSTEMS**

***Technical Study***

***Report Number: 2009/3***

***Date: March 2009***

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## ACKNOWLEDGEMENTS AND CITATIONS

This report describes upgrade of a computer programme for calculating the cost of CCS systems sponsored by the IEA Greenhouse Gas R&D Programme. This report was prepared by:

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To ensure the quality and technical integrity of the research undertaken by the IEA Greenhouse Gas R&D Programme (IEA GHG) each study is managed by an appointed IEA GHG manager. As this work was an upgrade of an existing computer program no external review was performed.

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The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "Upgraded calculator for CO<sub>2</sub> pipeline systems, 2009/03, March 2009".

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# UPGRADED CALCULATOR FOR CO<sub>2</sub> PIPELINE SYSTEMS

## **Background**

IEAGHG had a cost calculation computer program for CCS systems developed by Woodhill Engineering<sup>1</sup> some years ago (ref report PH4-6). This enabled high level cost estimates to be made of CO<sub>2</sub> capture and storage systems and was based on Excel. Within this spreadsheet was a routine for calculating the cost of CO<sub>2</sub> trunk lines which was found to have a sizing routine based on oversimplified pressure drop equations and averaged physical properties of CO<sub>2</sub>. In 2006 a new model, based on another spreadsheet, was developed for sizing and costing distributed CO<sub>2</sub> collection networks. This was done as part of the two studies which were undertaken on distributed CO<sub>2</sub> capture and collection. It was felt that the CO<sub>2</sub> trunk line sizing routine should be improved and that at the same time the pipe network design program should be made available as part of the calculation suite.

## **Study approach**

A contract to develop and upgrade the original Woodhill program and the network program was awarded to Gastec UK/AMEC who had already produced the new network design program. After obtaining the original code from Woodhill-Frontier options were examined and it was felt that as both programs were Excel based it would be simplest to amalgamate them into one program using the original Woodhill interface where possible. The possibility of adding a graphical map based interface for the distributed collection network was investigated as an additional option but although possible the necessary licence for commercial use was found to be too costly. It was on this basis that Gastec UK/AMEC proceeded with the development of the upgraded calculator.

## **Results and Discussion**

The contractor developed a new pressure drop calculation procedure for CO<sub>2</sub> trunk lines segmenting the lines into 40 elements of equal length to account accurately for compressible flow. Calculations are based on turbulent flow with the internal pipe roughness of typical carbon steel line pipe. Tables of the physical properties of pure CO<sub>2</sub> (Density and viscosity) are used as the basis for the calculations. The range of valid temperatures and pressures covers from -50 to +75 °C and from 1 bara to maximum 1000bara pressure<sup>2</sup>. Intermediate values in the tables were obtained by interpolation. Consideration was given to allowing different CO<sub>2</sub> purities but this was found to seriously complicate the calculation as a full multi-component physical property routine would have to be acquired and built in. Calculations are based on isothermal conditions with no change in elevation.

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<sup>1</sup> Now Woodhill Frontier following a take over

<sup>2</sup> Below 0°C max pressure 700bara and below -25°C max pressure 300bar



Other additional features over the original calculator are a greater choice of terrain types and the ability to set percentages of each type of terrain. It is also possible now to specify the count of road/rail/river crossings which are then taken into account in the cost estimate. The contractor also introduced routines to allow costs to be escalated using any of the four main published industrial construction cost indices, the possibility to calculate costs in different currencies default exchange rates which can be overridden. The ability to adjust costs for different world regions using regional cost factors was retained and extended to the other parts of the model.

Because of the intricacy of the original trunk line sizing routines which included sizing/costing of gas and hydrogen lines the improved sizing/cost routine was added as an option leaving choice of the old less accurate routine intact so that users could still make comparisons with earlier estimates. The user can still use the system to cost complete CCS systems but with the new CO<sub>2</sub> pipeline sizing and costing routine.

Alternatively users can select an option to size and cost CO<sub>2</sub> trunk lines individually using a separate input sheet. When used in this mode graphical representations of conditions along the pipeline are displayed. The routine calculates the requirements and costs for booster compression or pumping as did the original model but also now includes metering and block valve costs as well. Pipeline costs are based on statistical data from pipeline projects collected by AMEC and are derived from lookup tables. The cost data indicate that for smaller diameter lines there is little difference in total installed cost and the table groups some diameters together. The model has been run on some typical CO<sub>2</sub> pipelines varying diameter to change the number of pumping/compression stations needed. The results are shown graphically in fig 1 and 2.

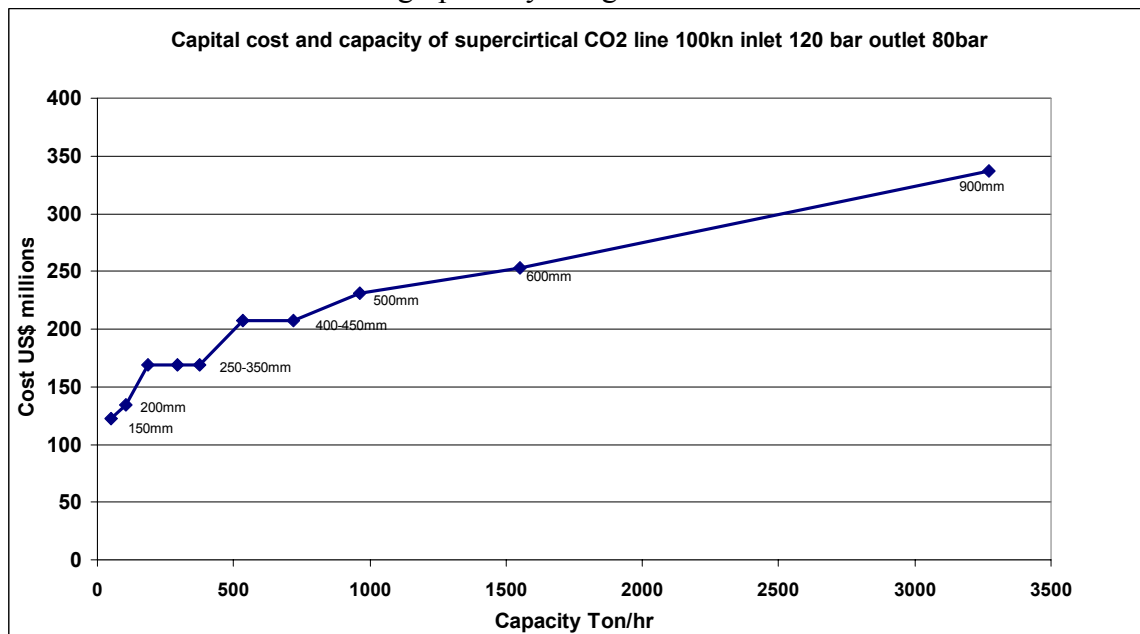
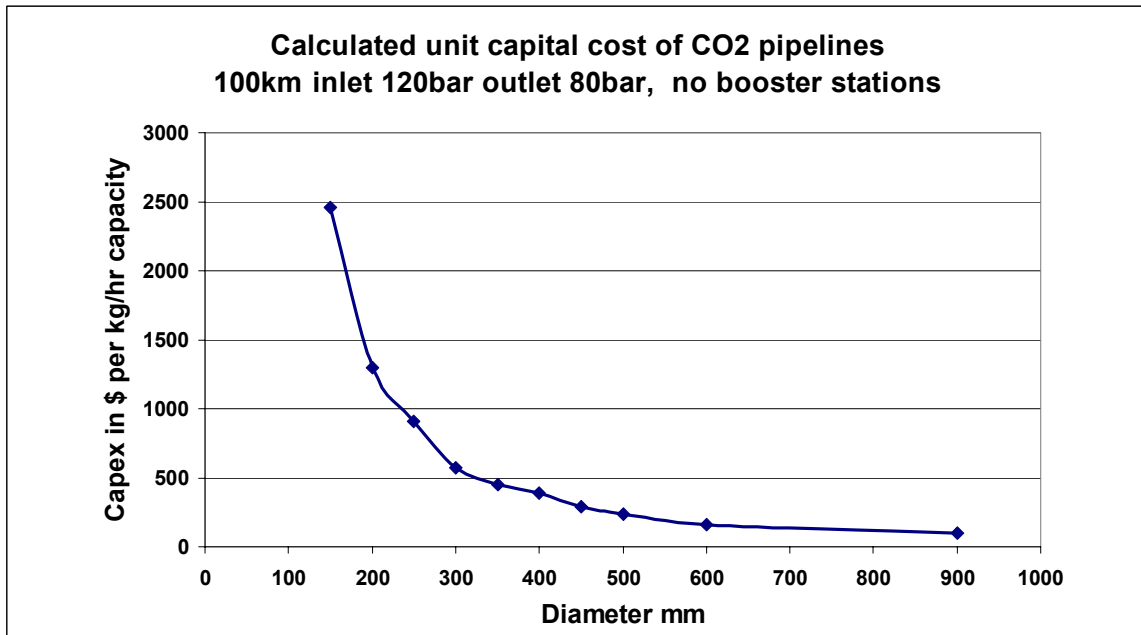
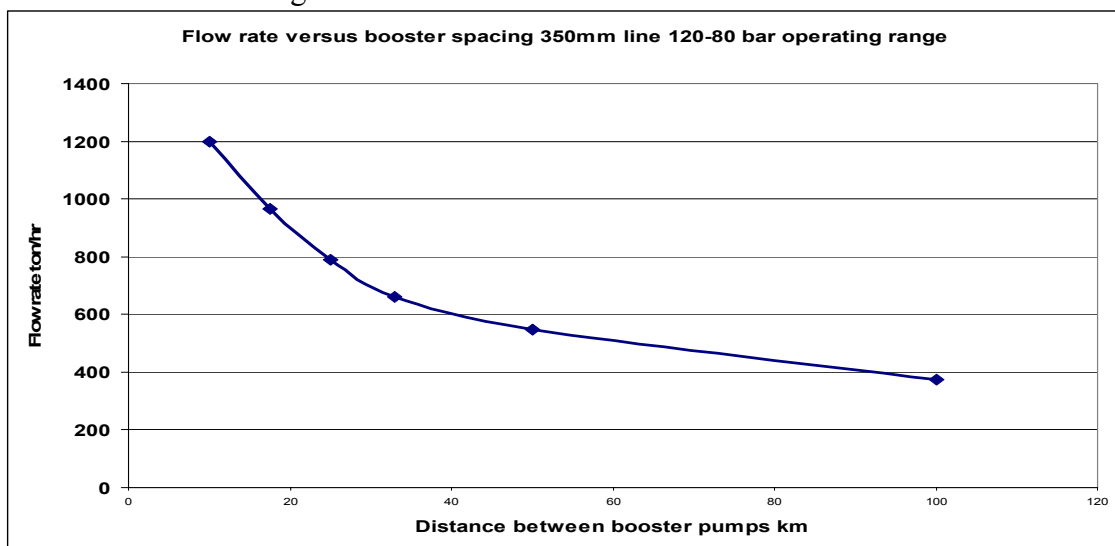


Fig 1 Capital cost v capacity for a 100km supercritical CO<sub>2</sub> line



**Fig2 Unit capital cost for a CO<sub>2</sub> line as function of diameter**

The sizing routine was run with increasing flows which requires an increasing number of booster pumping stations. The effective unit capital cost of the capacity was calculated including operating costs discounted over 20 years. The results based on these costs from the model for installing and operating such pumping stations showed that pumping was in general a cheaper way of increasing capacity than installing larger lines. This is not a surprising conclusion given that pumping power and pump costs are much less than compression power and costs for gaseous systems. However although this analysis shows lower cost it would be operationally much more burdensome. The results for several sizes of line are shown in Fig 3 and 4 below.



**Fig 3 Variation of pipeline capacity with booster spacing**

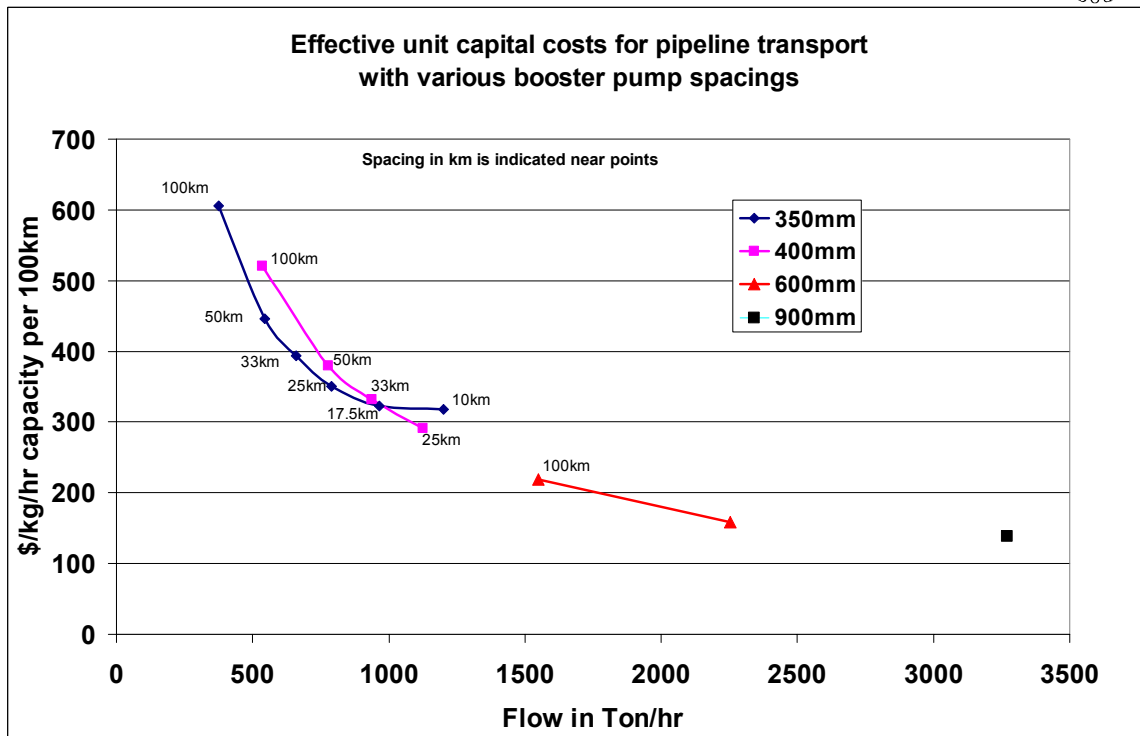


Figure 4 Variation of effective unit capacity costs with diameter and pump station distance

The last option now available is to design, size and cost low pressure distributed CO<sub>2</sub> collection networks. This is a stand alone part of the suite which uses the network design model developed by AMEC/Gastec-UK. Its main application is for the design of systems to gather CO<sub>2</sub> from clusters of smaller industrial sources of CO<sub>2</sub>

Documentation for the calculator is in the form of the original built in help file plus a new guidance document explaining the changes made and how the user can use the additional features.

### Expert reviewers comments

The calculator was checked internally and not subject to formal external review. It is recognised from the internal reviews that the calculator needs to be used by experienced engineers and an AMEC project team has already used the new elements successfully for a major CO<sub>2</sub> collection infrastructure project as a test case

### Conclusions

The revised cost and sizing calculator now allows more accurate high level sizing and costing of CO<sub>2</sub> pipelines and collection systems. It is not intended as a final pipeline design tool for which specialist pipeline sizing routines must be used able to cater for



terrain height changes and the physical properties of the actual CO<sub>2</sub> gas compositions. The tool is now available for use. IEA GHG will maintain a log of comments and suggestions from any users so that any errors found can be corrected and useful improvements added if the amount of use and extent of suggestions warrants.

To use the revised model copy the excel file and help file which are in a subdirectory of the CD into the same directory on your computer. Open the excel file. Help on the basic functions is available through the help button or via the drop down menu (Cost Estimation Model.) Information on how to use the network design tool is to be found in a separate set of instructions in an appendix to this document entitled “Network model Instructions”. Information about the upgraded features is to be found in the report on the upgrade which follows this introduction





GaC Contract No. 3626  
 AMEC Contract No. 1663A



**Project Upgrade of CO<sub>2</sub> Pipeline Cost calculation Programs**

**Document No. 1663A-020-000-RPT-001**

**Revision P**

**Upgrade of CO<sub>2</sub> Pipeline Cost  
 Calculation Programs (IEA/COM/07/138)**

<b>P</b>	<b>Preliminary</b>	JW	11/03/08					IRS	20/03/08
<b>Issue Rev</b>	<b>Issue or Revision Description</b>	<b>Origin By</b>	<b>Date</b>	<b>Chkd By</b>	<b>Date</b>	<b>Appd By</b>	<b>Date</b>	<b>Appd By</b>	<b>Date</b>
		<b>AMEC</b>						<b>OTHER</b>	



**GaC Contract No. 3626**  
**AMEC Contract No. 1663A**





**Project Upgrade of CO2 Pipeline Cost calculation Programs**

**Document No. 1663A-020-000-RPT-001**

**Revision P**

REVISION CHANGE NOTICES

Rev.	Location of Changes	Brief Description of Change
P	Original Issue	Original Issue



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## 1.0 INTRODUCTION

### 1.1 Project Overview

The IEA Greenhouse gas R&D program has two Excel based computer programs developed which estimate the cost of pipelines carrying CO<sub>2</sub>. The first is a model built by Woodhill Engineering which includes routines for CO<sub>2</sub> trunk pipeline as well as for other fluids and also injection wells and capture plant. The pressure drop and line sizing routines in this model are considered to be inaccurate, especially under supercritical conditions.

The second model was recently developed by GASTEC at CRE Ltd and AMEC. This model calculates the costs of lower pressure CO<sub>2</sub> collection networks and is calibrated for UK costs. The purpose of the work is to upgrade both of these models and to integrate them into one.

### 1.2 Objective

The existing Woodhill program has a form based user interface whereas the Gastec/AMEC program is currently based on filling in a spreadsheet. In order to make the programs more user friendly a similar interface is required for this latter model.



In summary, the aims of the project are:

- to increase the technical veracity of the trunk pipeline model, and
- to improve the user interface amenability of the network model,

Thereby make them more complementary and better aligned to ensure seamless integration.

### 1.3 Integration Method

The resulting package does not fundamentally change the way the separate models worked. It is important not to disturb the coding and behaviour behind each model lest the validation of each part is lost. They have been integrated under the same visual style and a new control panel added, this is the only way the two models interact. The new trunk line routine is a stand alone calculation form which both models connect to, again to limit the interaction between models.

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## 2.0 SCOPE OF WORK

### 2.1 IEA GHG Defined Scope

There were two defined activities with separate scopes of work. Firstly the modifications to the Woodhill programme, secondly the integration and refinement of the AMEC/GaC programme.

### 2.2 Woodhill Programme PH4-6



The Woodhill cost model enables costs of complete CCS projects to be estimated. As part of the model, trunk line segments for pipelines carrying CO<sub>2</sub>/H<sub>2</sub> and natural gas can be calculated. The CO<sub>2</sub> pipeline cost figures generated by this model are considered insufficiently accurate. They use very simplistic assumptions about the fluid properties of CO<sub>2</sub> and use a very simple model for line sizing and costing.

1. Provide computerised information on CO<sub>2</sub> PVT and transport properties for use in accurate pressure drop and trunk line sizing to cover the full range of temperatures and pressures likely to be used in CCS projects. The range should be for pressures to at least 200 bar and temperatures from -20°C to +40°C.
2. Select a pipeline pressure drop and line size calculation routine suitable for dealing with long CO<sub>2</sub> trunk lines, compressible flow including supercritical conditions. It is expected that calculations will have to be based on splitting the lines into a number of sections because of the widely changing PVT conditions along the lines which are likely to be encountered.
3. Select a suitable basis for cost estimation of long trunk lines to include all the key parameters which affect cost including but not limited to:
  - Terrain type
  - World region
  - Steel price
  - Design margins
  - Compression stations
  - Additional features
  - Cost index

For terrain type to be able to specify % of each of several terrain types per segment.

For world region to consider 4 or 5 main construction cost regions.

For steel price to have a standard default value, (or values if each region is different).

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Design margins refer to the different design stress margins applicable in areas of differing population exposure.

Additional features refers to such items as block valves, pigging facilities, leak detection monitoring.



Cost index refer to use a base index so that costs can be adjusted to allow for cost escalation with time. Use a separate index for pipelines and compression facilities.

4. Unlock the visual basic code used in the calculators (Password is case sensitive IEA2611). Re-programme the input sheet for CO<sub>2</sub> lines to include the extra input requirements and to allow for lines to be broken into appropriate number of segments. Note that the routines for Fuel/feed pipelines are to be left unchanged. Currently a selection of CO<sub>2</sub> or other gas is made on the pipeline branch input form. As the new CO<sub>2</sub> pipeline routine will be more detailed either a separate input form or additional detail on the existing input form will be required.
5. Re-programme the code to incorporate the new calculation routines. Calculations of each segment based on isothermal conditions. One temperature specified for each segment.
6. Modify the output sheets to reflect the additional data generated.
7. Include a graphical representation of pressure and density conditions along the line segment.



### 2.3 GaC/AMEC programme

The routine produced by Gastec/AMEC covers only UK construction costs. The work will include extending the programme to cover costs in a number of other regions. In addition the costs for compression stations should have the option for stand alone or being integrated on site with capture facilities. At present they assume a stand alone site has to be provided.

1. Collect data necessary to use the existing model for a selection of other world regions. Group countries by region. Use 5-6 regions.
2. Modify programme to allow selection of alternative regions
3. Include cost index calibration point with possibility for users to apply a suitable global escalation index.
4. Define default currency exchange rates which are applicable at the time of set up. For each region select an appropriate currency in which results are reported by default, £, € and US\$ should suffice. Include option to report in alternative currency using the fixed default exchange rates, which shall be displayed.

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5. Integrate the spreadsheet into the Woodhill model calculator and add input and output form or forms of similar style and appearance. Ensure that the worksheets in which data are entered are also accessible e.g. with a toggle so that they can be viewed.

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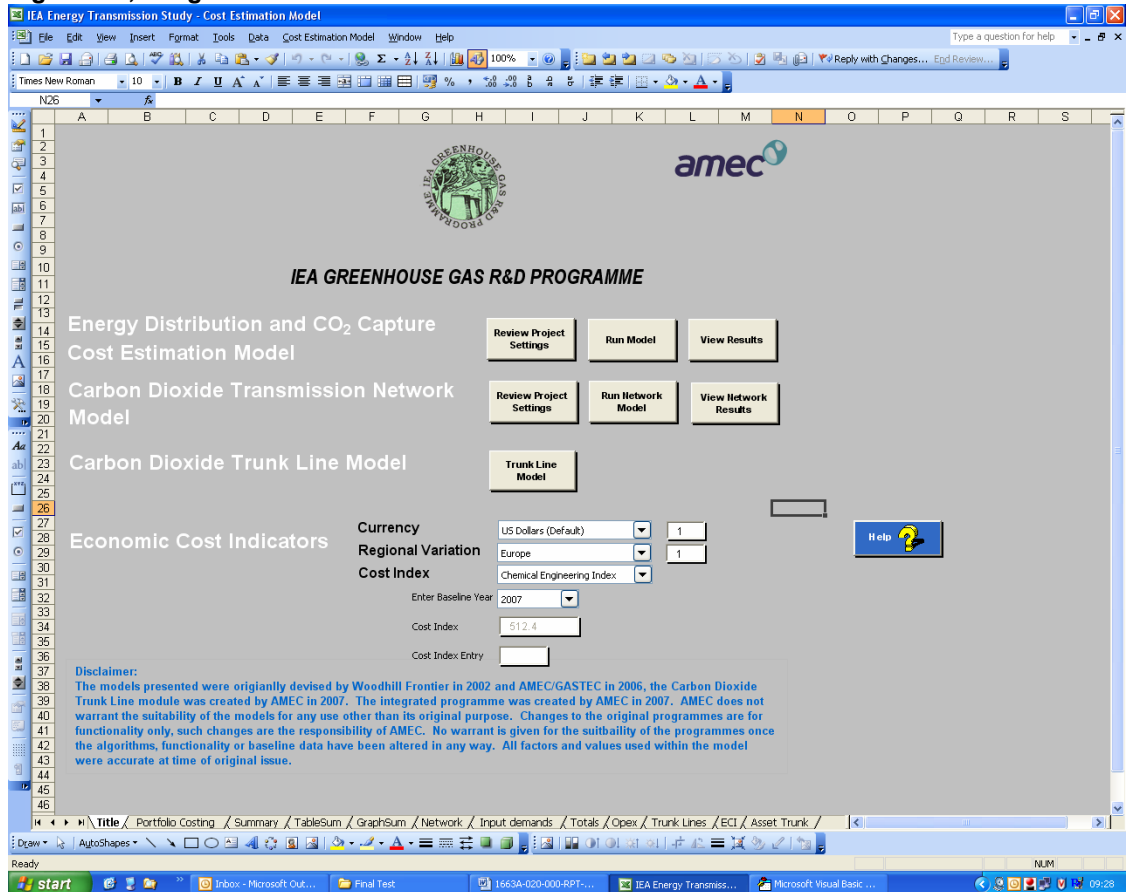
### 3.0 Introduction to the models and the integrated package

The new model consists of three parts;

- Energy Networks – the Woodhill Model
- Carbon Dioxide Network – AMEC model
- Trunk Lines

Each is a distinct part to the model with limited interaction. The models are accessed by a simple dashboard, Figure 3-1, directing the user to the models and the cost index tool now included.

**Figure 3-1, Integrated Dashboard**



Selections can be made from the dashboard to edit settings, view results and run the model. Project settings for the network model are also the project settings for the Trunk Line model. Once selected the model runs as per the original model with the minor modification operating alongside.





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## 4.0 Changes to the network model

### 4.1 Network model inputs

The major change to the original network model is cosmetic, the previous format has been updated to provide a consistent format over the whole model. As part of this the input format has been changed slightly with project wide variable being consolidated in one place. The network model section is now three forms;

- Network – sets the default values and conditions
- Input Demands – data entry for emitter information and low pressure elements of a network.
- Input Pipelines – data entry for the network pipelines information

Reference should be made to the original models' reports for operating instructions in greater detail.

### 4.2 Network

The network page, Figure 4-1, allows the user to adjust the network models defaults for operating pressures, block valve distances and operational expenditure variables. Pipe sizes are also included on this page, but it is recommended that no changes be made to this table.

**Figure 4-1, Network Settings Form**

The screenshot shows a spreadsheet titled "IEA GREENHOUSE GAS R&D PROGRAMME Carbon Dioxide Transmission Network Model Network Preset Options". It contains several sections of data:

**Carbon Dioxide Transmission Networks**

The network model requires a number of presets to be defined in order to function, this page consolidates those variables.

Pressure: The inlet and minimum outlet pressure define the pipe size and are typically set to 100 barg and 80 barg respectively. In considering pressure 100barg should be considered the absolute minimum for high pressure systems in order to avoid supercritical issues with the Carbon Dioxide.

Block Valves: The separation distance default should be 15km for High Pressure and 50km for medium pressure.




Operational Expenditure: The default of 2%, 5% and 6\$/GJ is a basic assessment on typical systems. Adjustments can be made based on operating regime or local experience.

Pipeline Size Criteria: The defaults are standard pipesizes and whilst it is possible to adjust the sizes it is not recommended.

Network Design Options		Pipeline Size Criteria				
Option	Value	Size Number	Steel Nominal	Steel Internal	PE Nominal	PE Internal
High pressure system	Initial Pressure: 110 barg Minimum Outlet Pressure: 80 barg					
Block valve separation distance	High pressure systems: 15000 meters Medium pressure systems: 5000 meters	1	60.3	50.8	63	52
		2	88.9	76.2	75	61
		3	114.3	101.6	110	90
		4	168.3	152.4	160	131
		5	219.1	203.2	200	164
		6	273.1	254	250	205
		7	323.5	304.8	315	258

**Operational Expenditure**

Percentage operational costs for	Pipelines	2 %
	Compression and gas treatment	5 %
Energy costs	Cost per unit of energy	6 \$/GJ

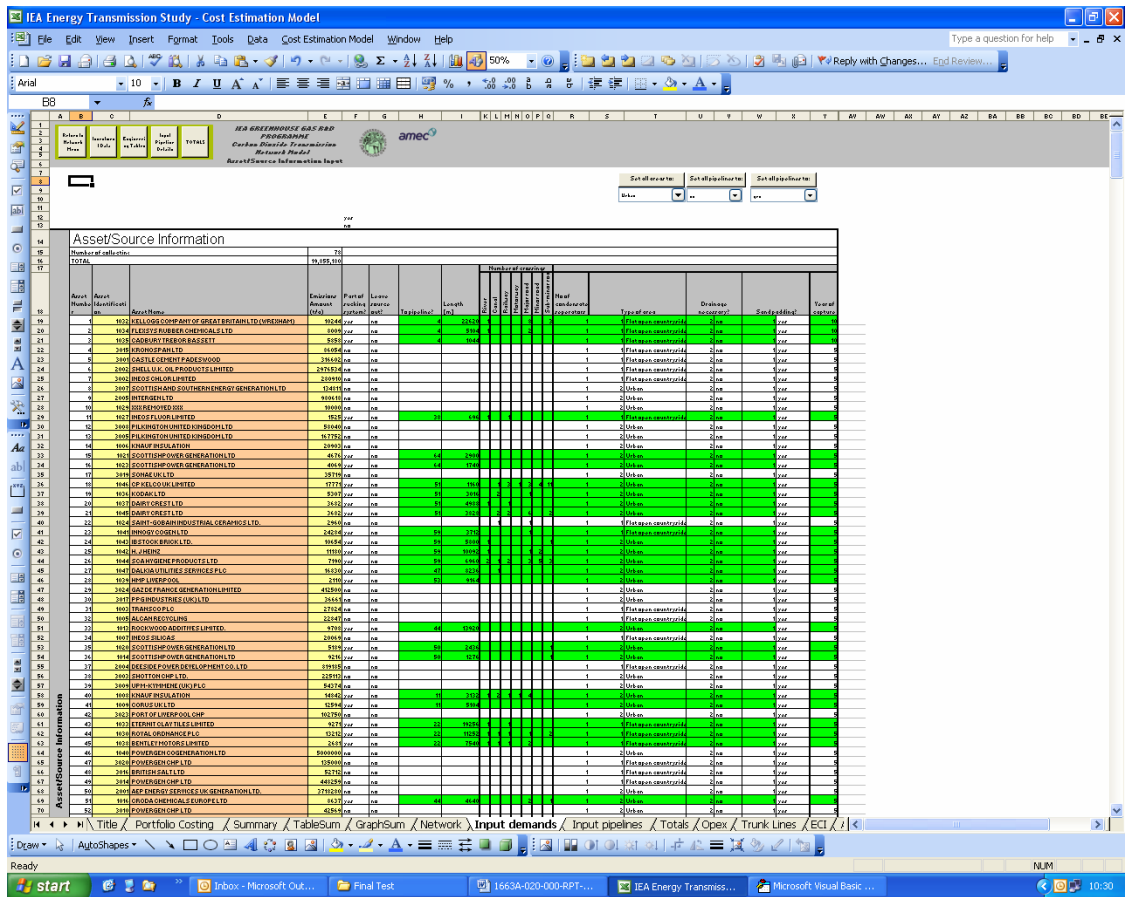
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### 4.3 Input Demands

The input demands form, Figure 4-2, is unchanged from the previous model apart from the cosmetic formatting. Here emitters are added and selected for low pressure service or into medium or high pressure routes.

For suction sources the pipeline length, crossings and terrain information is added and the model provides a pipe size. This information then feeds into the CAPEX model.

Figure 4-2, Input Demands Form



The screenshot displays the 'Asset/Source Information' table within the IEA Energy Transmission Study - Cost Estimation Model. The table lists various assets and sources with their respective details. The columns include Asset Number, Asset Name, Emittance (t/a), Part of process, Lower pressure, Length (km), Number of crossings, Type of service, Division category, and Size of capacity. The table is filtered to show assets with a 'Type of service' of '2.00' and a 'Division category' of '2.00'. The assets listed include various industrial and power generation facilities, such as 'HELLIOS COMPANY OF GREAT BRITAIN LTD', 'CARBURY THERMO ASSETT', 'CASTLE CEMENT FAREHAMWOOD', and 'SCOTTISH OVER GENERATION LTD'.

Asset Number	Asset Name	Emittance (t/a)	Part of process	Lower pressure	Length (km)	Number of crossings	Type of service	Division category	Size of capacity
1	HELLIOS COMPANY OF GREAT BRITAIN LTD	4724	no		0	0	2.00	2.00	2.00
2	CARBURY THERMO ASSETT	589	no		0	0	2.00	2.00	2.00
3	CASTLE CEMENT FAREHAMWOOD	3164	no		0	0	2.00	2.00	2.00
4	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
5	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
6	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
7	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
8	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
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14	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
15	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
16	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
17	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
18	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
19	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
20	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
21	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
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27	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
28	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
29	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
30	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
31	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
32	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
33	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
34	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
35	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
36	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
37	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
38	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
39	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
40	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
41	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
42	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
43	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
44	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
45	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
46	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
47	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
48	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
49	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
50	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
51	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
52	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
53	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
54	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
55	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
56	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
57	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
58	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
59	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
60	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
61	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
62	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
63	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
64	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
65	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
66	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
67	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
68	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
69	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00
70	SCOTTISH OVER GENERATION LTD	1418	no		0	0	2.00	2.00	2.00



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**4.4 Input Pipelines**

As with the previous page the changes to this sheet, Figure 4-3 are cosmetic. As before this sheet uses the emitter's ID number and the pipeline number to construct a network and size the entire network rather than the pipelines individually. As well as data entry this form also provides the results, in the form of line sizes.

**Figure 4-3, Input Pipelines Form**

The screenshot displays the 'Input Pipelines' form within the 'IEA Energy Transmission Study - Cost Estimation Model' software. The interface includes a menu bar, a toolbar, and a spreadsheet grid. The spreadsheet columns include: Number, Emitter ID, Pipeline Number, Collector flow (t/year), Length (km), Diameter (mm), Inlet pressure (bar), Outlet pressure (bar), Diameter (mm), Diameter (mm), Number of segments, Type of pipe, Diameter (mm), and Diameter (mm). The data rows are numbered 19 through 44. A large 'PROOF' watermark is overlaid on the spreadsheet data.

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**5.0 Trunk line model**

**5.1 User Interface and Operation**

The trunk line model is new and allows a single large pipeline to be considered in conjunction with a network from either model. Suitable for both Offshore and Onshore operation, the trunk line considers a long pipe in more detail than either of the previous models, splitting a pipeline into 20 segments and performing a segmental analysis of the pipeline.

The user inputs data in to the clear fields on the form, Figure 5-1, and a sizing routine will size the pipeline, calculate the pressure drop, operating conditions, compressor size and number and provide a cost estimate. It is possible for the user to manipulate the pipeline size to optimise the size required, the model does not automatically calculate the diameter this must be selected. The indicative table “Pipeline Size Guide” indicates the appropriate size for a preset velocity. For CO<sub>2</sub> systems it is recommended that the usual flow conventions apply, a maximum velocity of 20 m/s in the gas phase and 3 m/s in the liquid or supercritical phases.



**Figure 5-1, Trunk Line Data Entry**

The screenshot displays the 'IEA GREENHOUSE GAS R&D PROGRAMME Carbon Dioxide Transmission Network Model Trunk Pipe Line Results' window. It is divided into several sections:

- Data Entry:**
  - Pipeline ID: 10
  - Mass Flow, kg/h: 256000
  - Inlet Pressure, bara: 100 (supercritical liquid)
  - Inlet Temperature, °C: 15
  - Length, m: 80000
  - Yes/No: yes
  - Inlet Pressure: 10 (subcritical gas)
  - Outlet Pressure: 100 (supercritical liquid)
  - Booster Compressor Conditions:
    - Minimum Inlet Pressure: 90 (supercritical liquid)
    - Outlet Pressure: 100 (supercritical liquid)
    - Minimum Distance: 20 km
  - Diameter: 900mm
  - Segment Terrain Type %:
    - Flat open countryside: 0
    - Urban: 0
    - Mountainous: 0
    - Desert: 0
    - Forest: 0
    - Offshore: 100
    - River: 0
    - Canal: 0
    - Railway: 0
    - Motorway: 0
    - Major road: 0
    - Minor road: 0
    - Sub-minor road: 0
- Calculation Output:**
  - VP bar: 50.81
  - Outlet Pressure, bara: 99.781 (supercritical liquid)
  - Pressure Drop, bar: 0.219
  - Velocity, m/s: 0.193
  - Compressor:
    - Number of booster stations (including initial booster): 1
    - Actual Booster Compressor Spacing: [blank] km
- Pipeline Size Guide:**

Diameter vs Velocity	
20m/s	50
15m/s	80
10m/s	100
5m/s	125
3m/s	150
1m/s	300

The table opposite indicates pipe diameters for the normally accepted flow rates for gases and liquids. The table is a guide as to possible pipeline sizes

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## 5.2 Booster Stations

The model calculates the requirements for both the Initial Booster and Pipeline Booster stations should they be required.

Whilst initial pressurisation for a network would be covered within the network model, standalone pipelines or pipelines with long cross country runs may operate at higher pressures. If they do operate at higher pressures, then an initial booster will be required. The inlet and outlet pressures are allowed to transition the phase boundary however it is recommended that the outlet pressure is not specified below 90bar to avoid two-phase transition or flow in the pipeline.

For onshore pipelines it is often more efficient to provide periodic booster stations on a pipeline to maintain the pressure rather than run large low pressure drop pipelines. If this is the case then the model will calculate the number required and the distance between stations. For offshore pipelines the provision of boosters along a pipeline length is not practical as this would require entire offshore installations to be provided at a significant cost. Therefore offshore pipelines are best pressured at the beach and at the destination only. To provide for this condition the initial booster should have a high enough outlet pressure to ensure that the entire pipeline length remains above 90 barg. The model does not however calculate the power or cost of an offshore compressor installed in an existing structure for local well head pressure boosting.

The user simply has to set the Booster Station details selecting an inlet and outlet pressure or a minimum distance between stations. Using these criteria the model assess each segment of the pipeline and adds a booster station when the pressure drops below the compressors specified inlet pressure.

## 5.3 Terrain and Crossings

Terrain and crossing information is added to the model to adjust the costs accordingly. For terrain the percentage of terrain type for each pipeline should be added, taking care to ensure that it totals 100%. This methodology applies a factor based on the percentage to the pipeline cost. Crossings are added as the actual number of crossings of each type.

For offshore pipelines the offshore terrain should be the only terrain selected and the number of crossings should be zero.

## 5.4 Pipeline calculation

The pipeline calculation is based on a segmental approach dividing any pipeline into 20 distinct segments. Each section is subjected to the calculation routine and incorporated in the results. This approach gives a slightly more accurate approach than assuming one



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segment for the whole of the pipe as it allows at each segment the transport conditions to be correctly considered.

The methodology used is fairly robust and has been tested against established process simulation packages Aspen Plus and Hysys. The formula used in the calculation is used in the pipeline for both gas and liquid and it was found that by assuming isothermal conditions the same equation could be used for all physical states that may be experienced.

The formula in the general form is;

$$W^2 = \left[ \frac{g \times d \times A^2 \times \rho}{f_F \times L} \right] \left[ \frac{(P_1^2 - P_2^2)}{P_1} \right]$$

Where,

W = mass flow, kg/h

d = pipe internal diameter, mm

$f_F$  = Moody friction factor

L = pipe length, m

$P_1$  = absolute inlet pressure, bara

$P_2$  = absolute outlet pressure, bara

$\rho_1$  = inlet fluid density, kg/m<sup>3</sup>

And the following assumptions are made;

1. Isothermal flow occurs.
2. No mechanical work is done by the system and no mechanical work is done to the system.
3. Steady flow inside the pipe occurs.
4. The gas being conveyed is Ideal.
5. Velocity may be represented by average velocity at a cross section.
6. The friction factor being applied is constant along the pipe.
7. The pipe is straight and horizontal between the end points.
8. Acceleration can be neglected because the pipe is long.
9. Substance contained within the system assumed to be pure carbon dioxide.

The calculation examines each segment in turn and uses the previous segments results to drive the equation. As a value drops below the minimum allowed the routine adds a compressor and calculates the size and cost.



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### 5.5 Costing

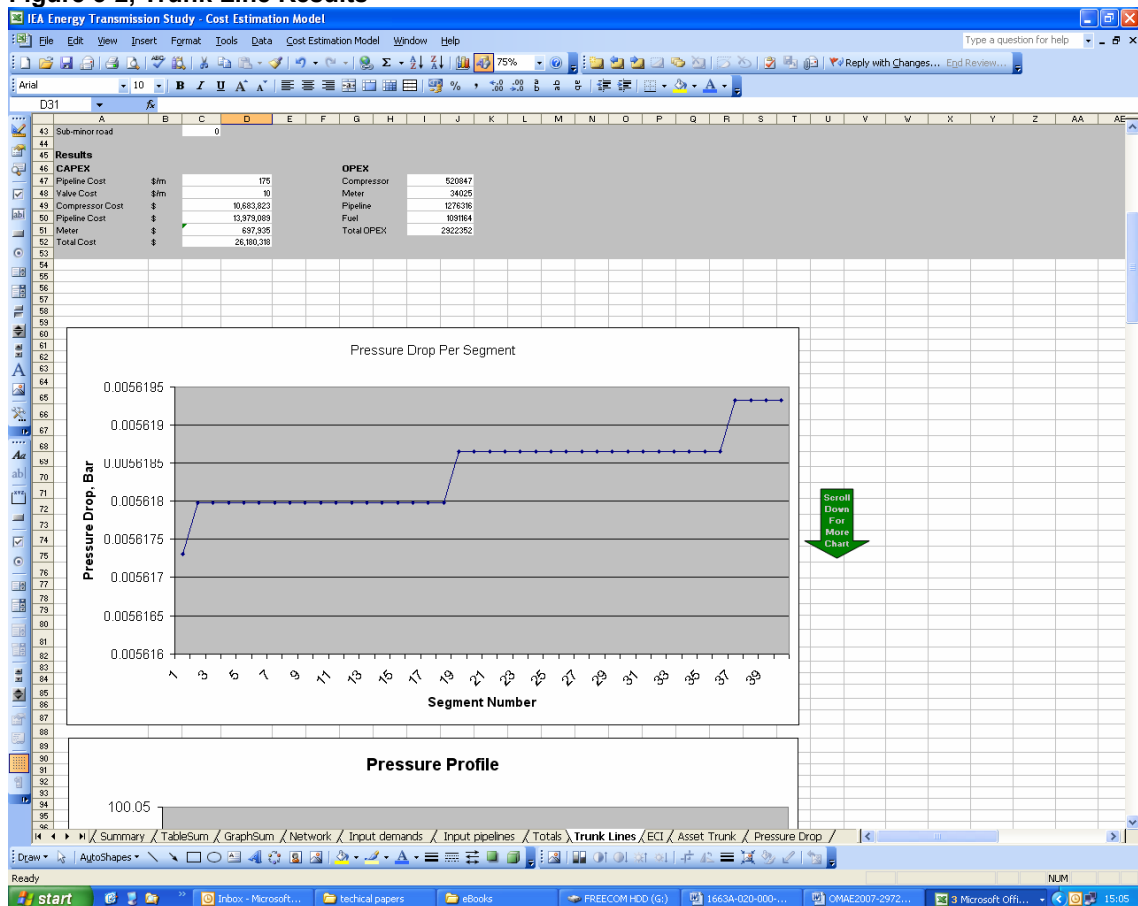
Costing of the pipeline uses the same cost information as the network model and the same factors. The trunk line model works by costing a pipeline and then applying factors according to Terrain, crossings, valves, cost indices changes and regional variations. There are no variables that can be manipulated for the trunk line model alone.

### 5.6 Results

The results are summarised at the bottom of the data entry table in the form of separate CAPEX and OPEX figures as illustrated below, Figure 5-2. Following this is a number of graphs;

- Pressure Drop per Segment
- Pressure Profile
- Pressure Drop Profile
- Density Profile

**Figure 5-2, Trunk Line Results**





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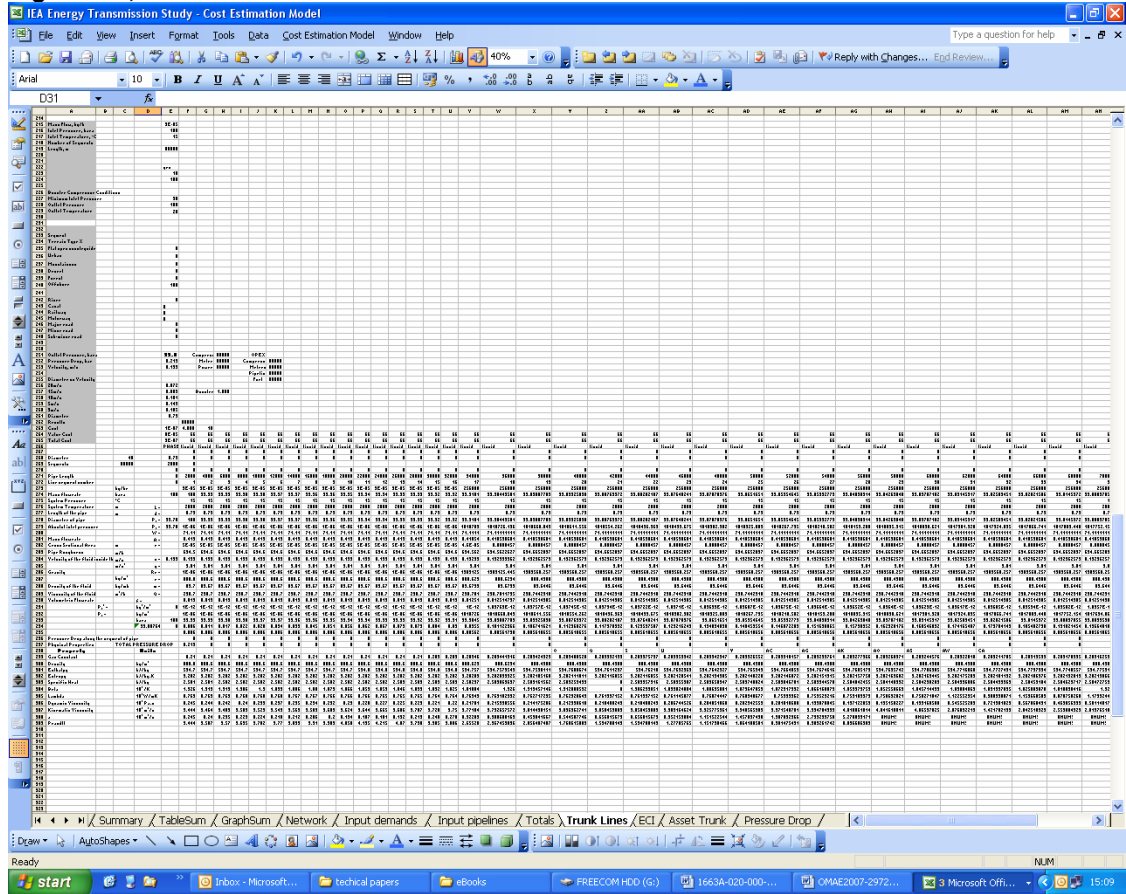
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In addition to the graphs the bottom of the page contains more detailed information, a copy of the calculation results by segment, Figure 5-3. This allows a competent user to examine the pipeline in detail and make changes to the input accordingly.

Figure 5-3, Detailed Trunk Line Results







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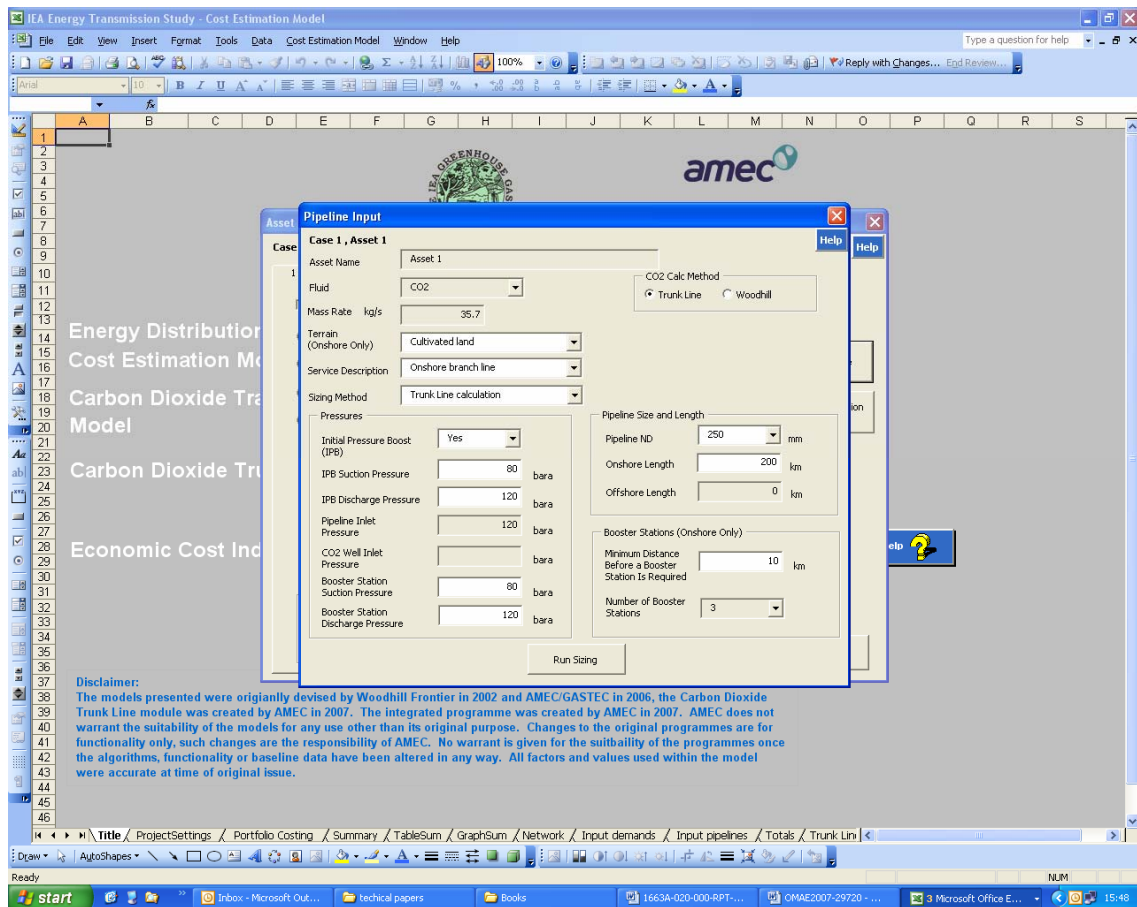
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**5.7 Interfacing with the Woodhill Model**

The Woodhill model previously used a set of fixed terms in its pipeline calculation. It is now possible to select either to use the previous methodology or select the AMEC trunk line calculation. The pipeline calculation entry form, Fig 5-4, has been modified to allow selection. Data entry is the same however by selecting “Trunk Line” the model applies the new methodology and reports the data back to the model in the appropriate format.

**Figure 5-4, Woodhill Model Pipeline Calculation Form**



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## 6.0 Economic Cost Indicators

The model now includes three economic factors, the first a regional variation, currency variation and a set of engineering cost indices. The regional variations are basic are simple multiplication factors to the baseline cost.

**Table 6-1, Regional Cost Factors**

Region	Cost Factor
Europe	1
UK	1.2
USA / Canada	1
South America	0.8
North Africa	0.8
Equatorial Africa	0.9
South Africa	0.7
Russia	0.7
Middle East	0.9
Indian Sub-cont.	0.7
SE Asia(excl.Japan)	0.8
Japan	1
China / Central Asia	0.7
Australia / NZ	1

Similarly currency factors are simple multiples.

**Table 6-2, Currency Factors**

Currency	Factor
US Dollars (Default)	1
Aus Dollars	1.21465
Euro	0.74955
Yen	117.86
UK Sterling	0.50985

For cost indices a number of systems are provided whilst partial data sets for Marshall & Swift and the Process Engineering Index are provided it is recommended that the Chemical Engineering Index should be used. The facility exists to edit or add to this data set as it becomes available by means of the sheet "ECI", Figure 6-1. This information is not however publicly available and journal subscription is generally required to access up to date indices.



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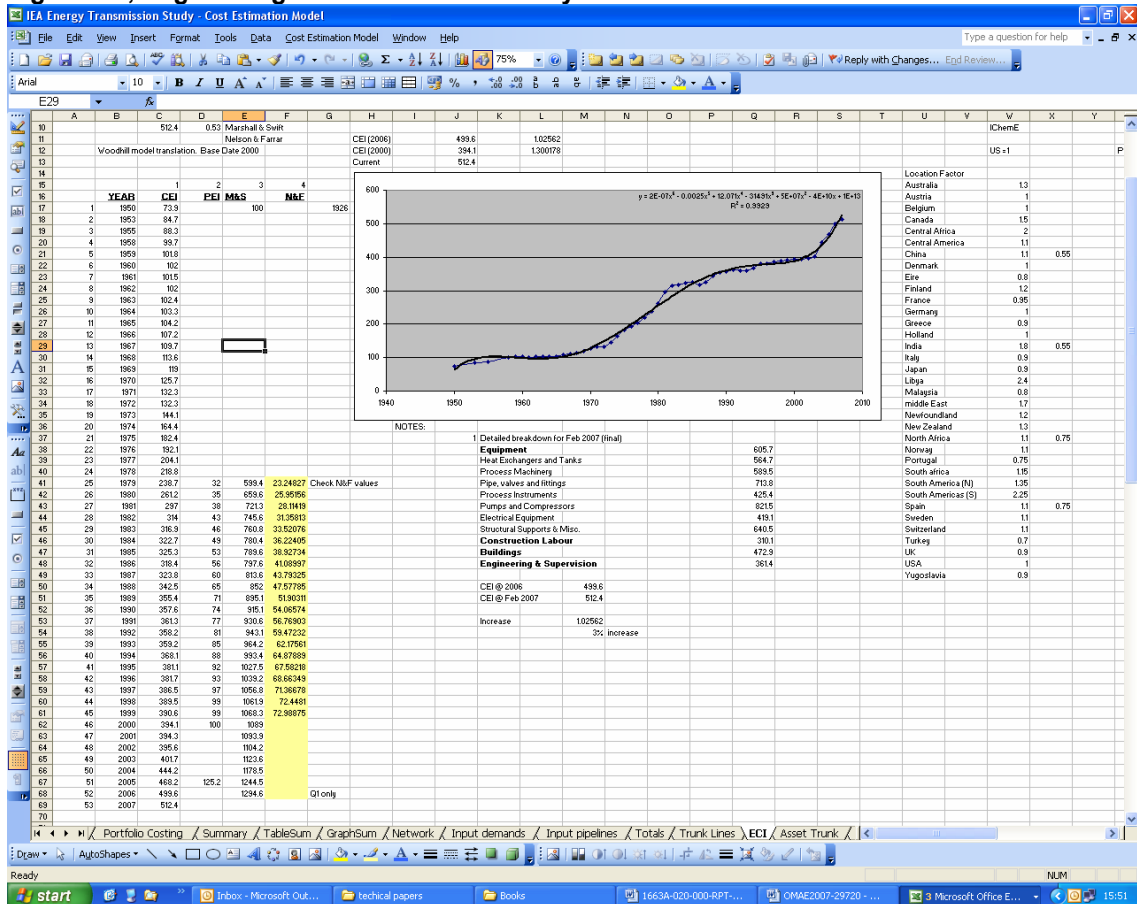


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Figure 6-1, Engineering Cost Indices Data Entry



**Appendix – Network Model Instructions (Extracted Appendix 6 of report 2007/12)**

## Appendix 6: Spreadsheet Instructions

The following section is a simple step by step guide intended to aid network designers who wish to use the design spreadsheet.

The spreadsheet will only tell a designer what size/material of pipe is required, pressures and costs, however a number of design decisions still need to be made. Prior to using the spreadsheet, the shape of the network to be designed should be determined and pipeline connections and distances should be established in the usual manner.

First of all, open a copy of the spreadsheet and save it under a new name e.g. Network1.xls. Now follow Steps 1 – X carefully to design your network.

### Step 1: Input Emission Sources

Ensure that the “Input Demands” tab is open.

nr	Identification	Name	Amount (t/a)	Part of sucking system?
86	74	1019 KIMBERLY CLARK LTD	6227	yes
87	75	1048 WARWICK INTERNATIONAL LIMITED	22500	yes
88	76	2003 POWERGEN UK PLC	2391870	no
89	77	1017 IBSTOCK BRICK LTD.	8057	yes
90	78	1002		no

Input the total number of sources to be included within your scheme in the yellow box next to “No of collecting points”. Next input the name of each source and give it a unique identification number e.g.

1001, 1002 etc. Input the emission (total to be collected) from the source in the column to the right of the name.

The distance required between shut-off valves can also be entered on this tab. Default values applicable to the United Kingdom are already set, but these can be altered.

**Network Cost \$/tonne 12.83**

Distance between valves (m)

Shut-Off Valves	
HP	1000
MP	2000

nr	Identification	Name	Amount (t/a)	Part of sucking system?	Leave source out?	To pipeline?	Pipeline Length [m]	Number of crossings						No of Condensate separators		
								River	Canal	Railway	Motorway	Major road	Minor road		Sub-sea power road	
13	1	1032		no	no											
14	2	1034 FLEXSYS RUBBER CHEMICALS LTD	8009	yes	no		4	5104	6	1					1	1
15	3	1035 CADBURY TREBOR BASSETT	5859	yes	no		4	1040	6	1					1	1
16	4	3015 KRONGSPAN LTD	86054	no	no										1	1
17	5	3001 CASTLE CEMENT PADESHOOD	316900	no	no										1	1
18	6	2002 SHELL U.K. OIL PRODUCTS LIMITED	2976534	no	no										1	1
19	7	3002 INEOS CHLOR LIMITED	280910	no	no										1	1
20	8	3007 SCOTTISH AND SOUTHERN ENERGY GENERATION LTD	134811	no	no										1	2
21	9	2005 INTERGEN LTD	980619	no	no				1	1					1	2
22	10	1029		no	no										1	2
23	11	1027 INEOS FLUOR LIMITED	1525	yes	no		30	696	6	1	1				1	2
24	12	3008 PILKINGTON UNITED KINGDOM LTD	58040	no	no										1	2
25	13	3005 PILKINGTON UNITED KINGDOM LTD	167752	no	no										1	2
26	14	1008		no	no										1	2
27	15	1021 SCOTTISHPOWER GENERATION LTD	4678	yes	no		64	2900	4						1	2
28	16	1023 SCOTTISHPOWER GENERATION LTD	4069	yes	no		64	1740	4						1	2
29	17	3019 SONAE UK LTD	35719	no	no										1	2
30	18	1046 CP KELCO UK LIMITED	17771	yes	no		51	1160	6	1	3	1	3	4	11	2
31	19	1036 KODAK LTD	5307	yes	no		51	3018	4	1					1	2
32	20	1037 DAIRY CREST LTD	3682	yes	no		51	4988	4	1					1	2
33	21	1045 DAIRY CREST LTD	3682	yes	no		51	3628	4	2	2				2	2
34	22	1024		no	no										1	1
35	23	1041 INNOGY COGEN LTD	24284	yes	no		59	3712	7						1	1
36	24	1043 BESTOCK BRICK LTD.	10854	yes	no		59	5206	6	1					1	2
37	25	1042 H. J. HEINZ	11180	yes	no		59	10992	7	1					1	2
38	26	1044 SCA HYGIENE PRODUCTS LTD	7190	yes	no		59	8960	6	2	1	2			3	2
39	27	1047 DALKIA UTILITIES SERVICES PLC	16830	yes	no		47	8236	7	1					1	2
40	28	1039 HMP LIVERPOOL	2110	yes	no		53	9164	5						1	2
41	29	3024 GAZ DE FRANCE GENERATION LIMITED	412500	no	no										1	2
42	30	3017 PPG INDUSTRIES (UK) LTD	36661	no	no										1	2
43	31	1003		no	no										1	1
44	32	1005		no	no										1	1
45	33	1013 ROCKWOOD ADDITIVES LIMITED.	9709	yes	no		44	13920	7						1	2
46	34	1007 INEOS SILICAS	20069	no	no										1	1
47	35	1020 SCOTTISHPOWER GENERATION LTD	5189	yes	no		50	2436	4						1	1
48	36	1014 SCOTTISHPOWER GENERATION LTD	9216	yes	no		50	1276	5						1	1

You will notice that there are further columns to the right of those that have been filled in, ignore these for the time being and proceed to the next step.

## Step 2: Input Pipe Distances and Connections

Ensure that the “Input Pipelines” tab is open.

Input the number of pipelines within the proposed network, the inlet pressure of the system and the materials of construction; this will open up the appropriate number of lines on the sheet for pipes.

The screenshot shows the 'Input Pipelines' tab in an Excel spreadsheet. Key input fields include:

- LP pipelines: Obligatory input, Optional input, No input
- Material: steel
- Inlet pressure of system: 10 Barg (bar gauge: overpressure)
- No of pipelines: 79
- HP system: in 110, out 80

A table on the right lists pipe specifications:

Nr	Steel		PE	
	Nominal	Internal	Nominal	Internal
1	60.3	50.8	63	
2	88.9	76.2	75	
3	114.3	101.6	110	
4	168.3	152.4	160	
5	219.1	203.2	200	
6	273.1	254	250	
7	323.9	304.8	315	

The main table below shows a network of pipes with columns for Number, No in scheme, Flows to, Pipe number, and Collecting from. Red circles highlight specific input fields and data points.

For each pipeline input it's allocated number in the scheme, any pipes that the pipe flows to (for pipes that flow out of the network input "0") and pipes that flow into that particular pipe. If a particular pipeline collects CO<sub>2</sub> from a source in the network, input the source ID (e.g. 1001, 1002) into the “Collecting from (no collecting point)” column. The inlet and outlet pressure of the high pressure system can also be input. The default values ensure that the CO<sub>2</sub> is in the supercritical phase.

The close-up shows the HP system input fields with 'in' and 'out' pressure values of 110 and 80 respectively, circled in red.

Next input the length of the pipeline, the predominant terrain that it crosses, any major crossings (e.g motorways etc) the number of condensate separators, and whether drainage or sand padding is required for the pipeline.

The screenshot shows a Microsoft Excel spreadsheet titled "Network Design Sheet Tiers 061&2 TRIMMED.xls". The spreadsheet contains a table with columns for flow, pressure, terrain, and various crossing types. A red circle highlights a row (row 13) with the following data points: Flow (m3/s) = 5104, Flow (t/a) = 0, Is HP allowed? = 1, Diameter (mm) = 603, and various crossing counts (River, Canal, Railway, Motorway, Motor road, Water road, Water road, Water road) = 1, 0, 0, 0, 0, 0, 0, 0, 0. The terrain is "Flat open countryside".

Flow (m3/s)	Flow (t/a)	Is HP allowed?	Diameter (mm)	Diameters	River	Canal	Railway	Motorway	Motor road	Water road	Water road	Water road	No of condensate separators	Terrain	Drainage	Sand padding?
5104	0	1	603	603	1	0	0	0	0	0	0	0	1	Flat open countryside	1	1

Note that if a pipeline crosses several different types of difficult terrain it is advisable to split it into several smaller pipes to gain an accurate cost for that section.

The default setting for the spreadsheet is to not allow high pressure lines in urban areas. This setting can be changed just above that column by setting all lines to yes (allow HP).

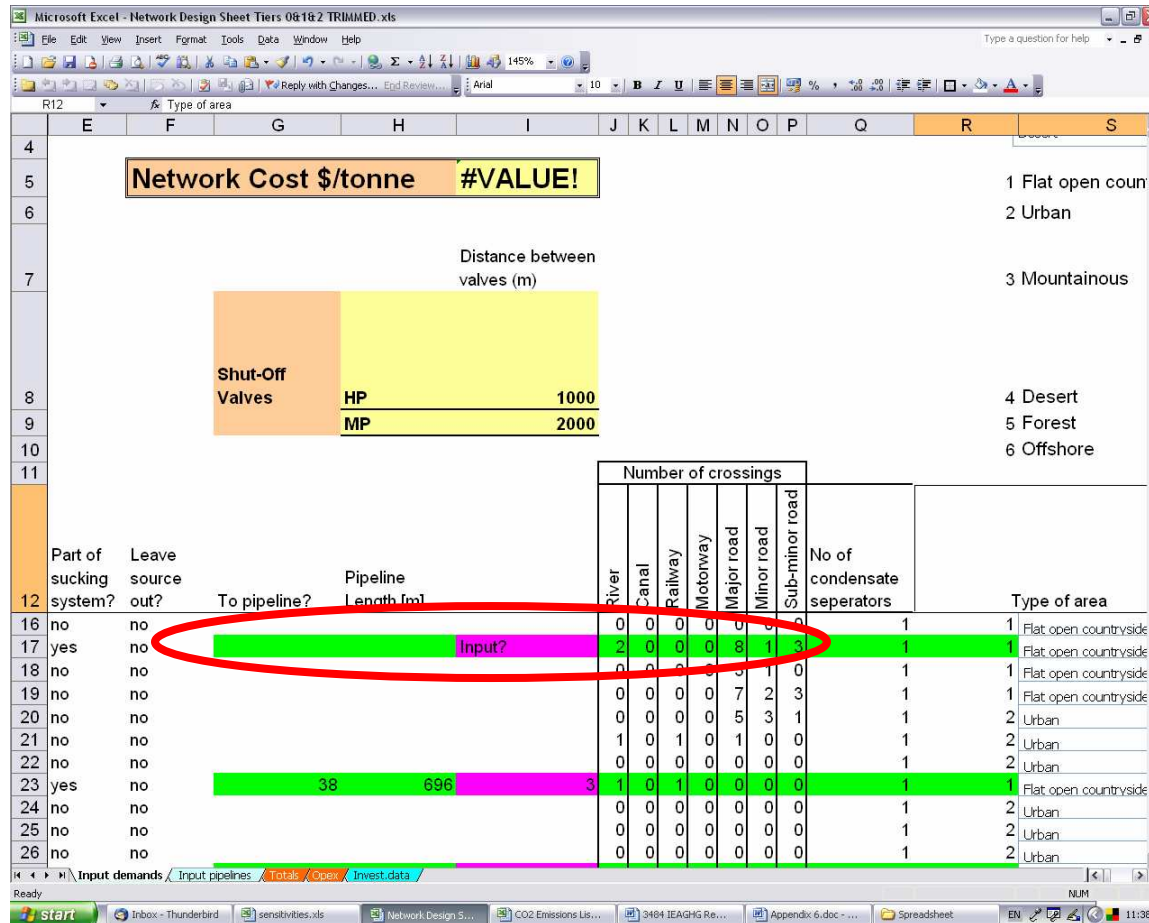
Care should be taken to ensure that all lines are entered correctly. Any mistakes in the data will affect the spreadsheet output. Once all data has been entered proceed to the next step.



### Step 3: Input Suction Network

Ensure that the “Input Demands” tab is open.

You will notice that the information relating to crossings etc has been transposed to this sheet. You can now select parts of the network to operate under a suction system. Choose a source to be included in the suction network and select “yes” in the “Part of Sucking System?” column. Some of the columns to the right of the source will change colour.



Input which pipeline the suction system is connected to for example if pipeline 1 is to be under suction and is connected to pipeline 2 you would enter a 2 in the “To pipeline?” column. Enter the length of the pipeline in the adjacent column. The purple column should now change; if it reads “n.a”, then a suction pipeline is not possible for this source either because of the size of emission or the distance to be travelled means that the pipe required is too large. If a suction pipe is not feasible for a particular source ensure that the “Part of sucking system” column is returned to “no”.

Once this stage is completed all information relating to sources and pipelines should have been entered into the spreadsheet.

### Step 4: Interest, Plant Lifetimes and Operational Costs

Ensure that the “Totals” tab is open.

From this tab the plant lifetimes and interest rate can be changed depending upon the particular circumstances applicable to the network being designed.

	Investment	Life me
Pipelines	\$356,310,915	30
Crossings	\$1,841,100	30
Separators	\$48,000	30
Compressors	\$1,375,314,107	25
Suction system	\$40,899,548	30
Meters	\$17,084,262	25
Vaives	\$15,537,984	30
Drying	\$154,314,784	25
<b>Total</b>	<b>\$1,961,350,701</b>	
<b>Interest rate</b>	<b>5.0%</b>	
<b>OPEX</b>	<b>\$116,174,713 /year</b>	
<b>Capital cost</b>	<b>\$136,715,866 /year</b>	
<b>Total</b>	<b>\$252,890,580 /year</b>	
<b>Total</b>	<b>\$12.83 /ton</b>	

Next ensure that the “Opex” tab is open.

From this tab the operational costs can be estimated. It is possible to change the percentage operational cost from capital cost and the cost of energy for compression.

Microsoft Excel - Network Design Sheet Tiers 0&1&2 TRIMMED.xls

Picture 5

Logos: GASTEC at CRE, kiwa Partner for progress, amec, IEA GREENHOUSE GAS R&D PROGRAMME

OPEX

% investment pipelines	2%
% investment compressors	5%
Cost energy (\$/GJ)	6
OPEX	- \$/year 116,174,713

Input demands / Input pipelines / Totals / Opex / Invest\_data

