H_2-BASED IRONMAKING

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NEO CARBON ENERGY

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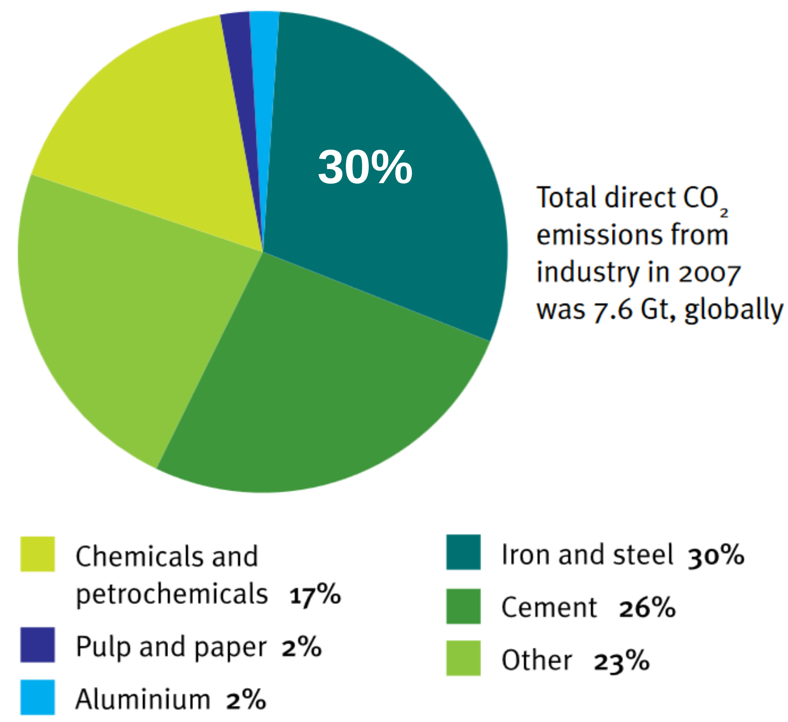
Background & scope

- Iron&steel sector is a marked contributor to CO_2 emissions from industry
- VTT has studied options for significant emissions reductions in iron&steel industry in several projects and developed a feasibility evaluation tool
- One important alternative was missing: Iron ore can be reduced with H_2 enabling virtually CO_2-free iron/steel



Data: IEA Energy technology perspectives 2010
Fig: [Reducing CO2 emissions from heavy industry 2012]

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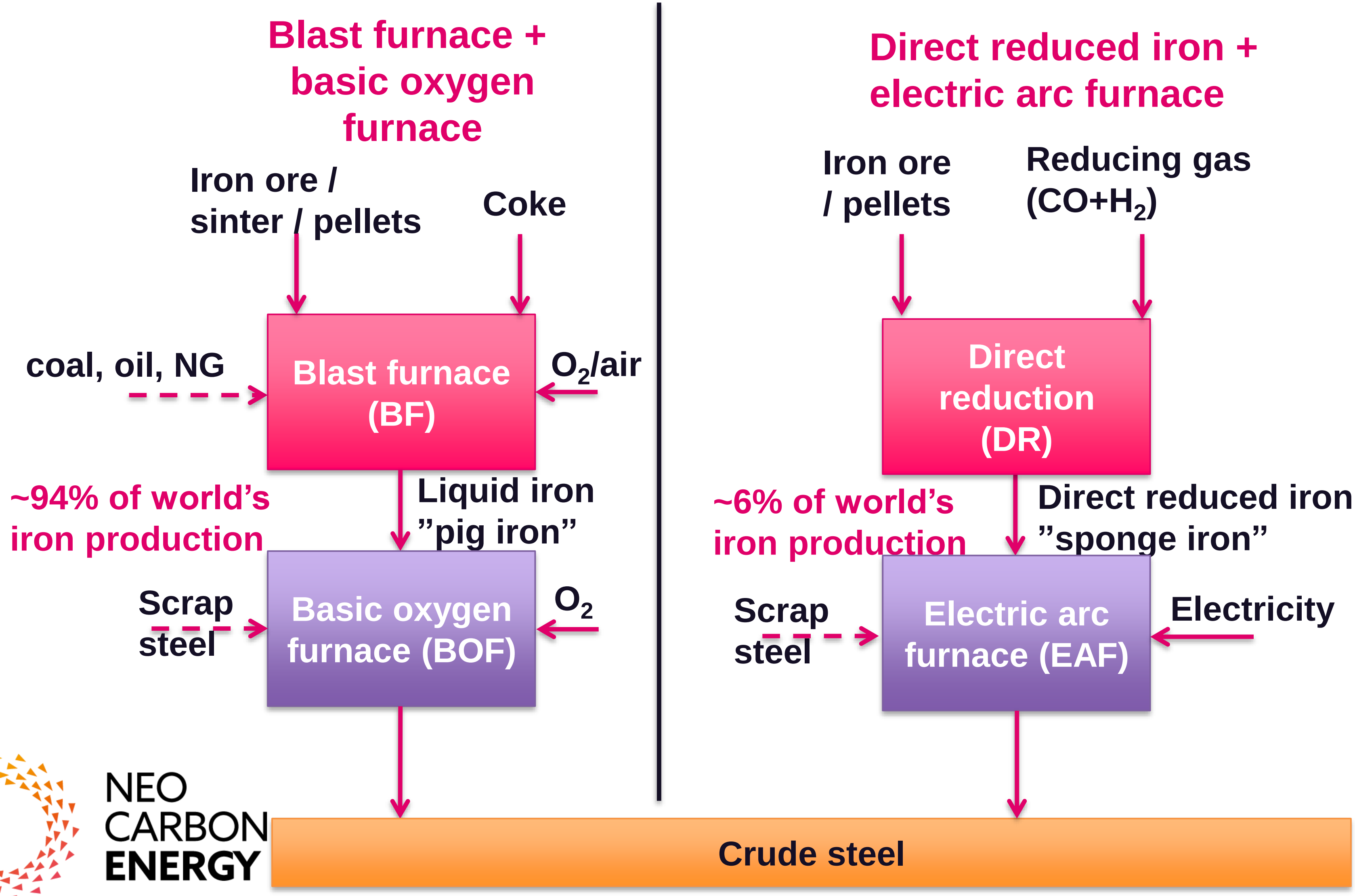
STEEL PRODUCTION

Primary(=ore-based) steel production



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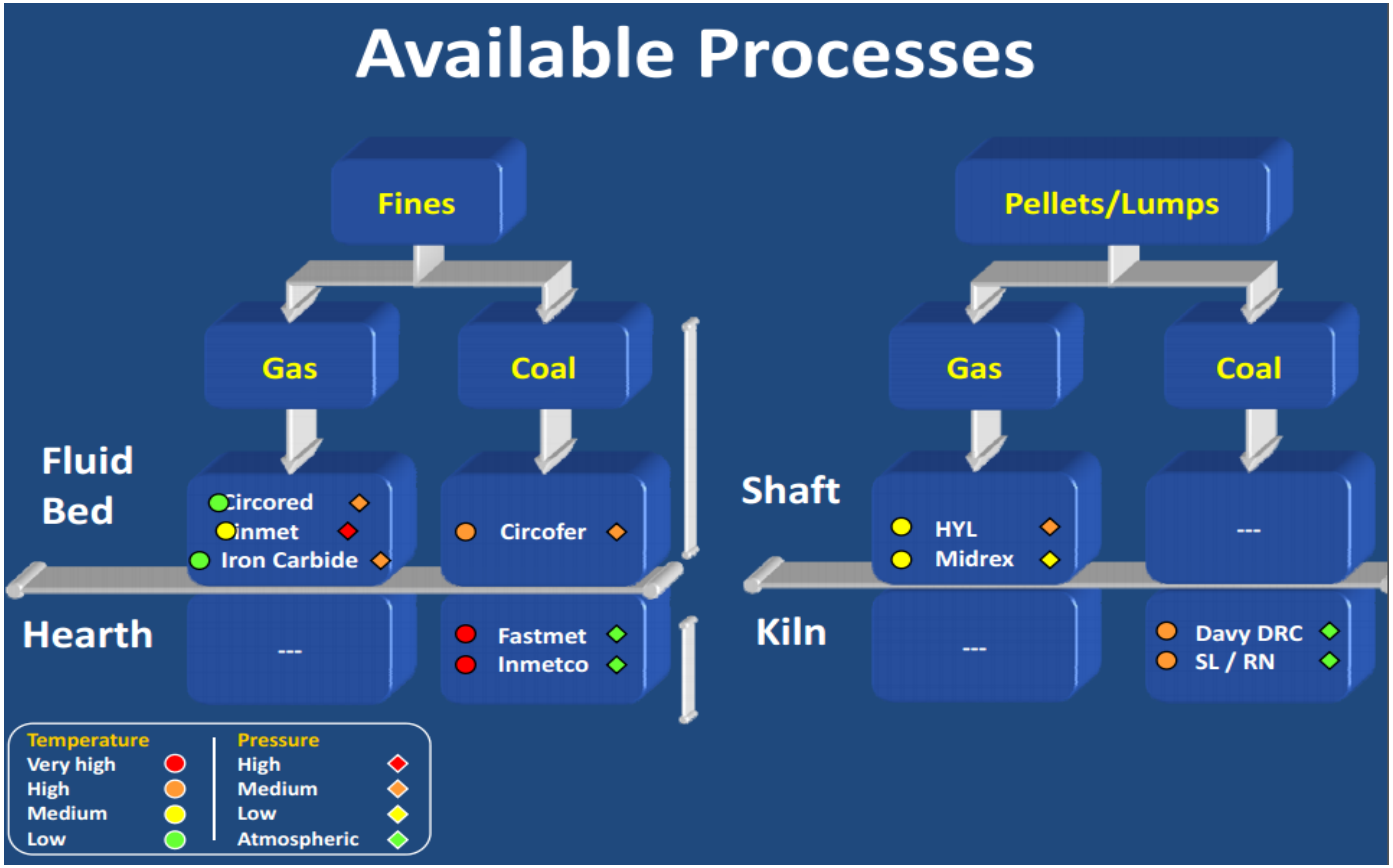
Direct reduced iron

Various process alternatives



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http://metallics.org.uk/dri/

MIDREX – The most common DRI process

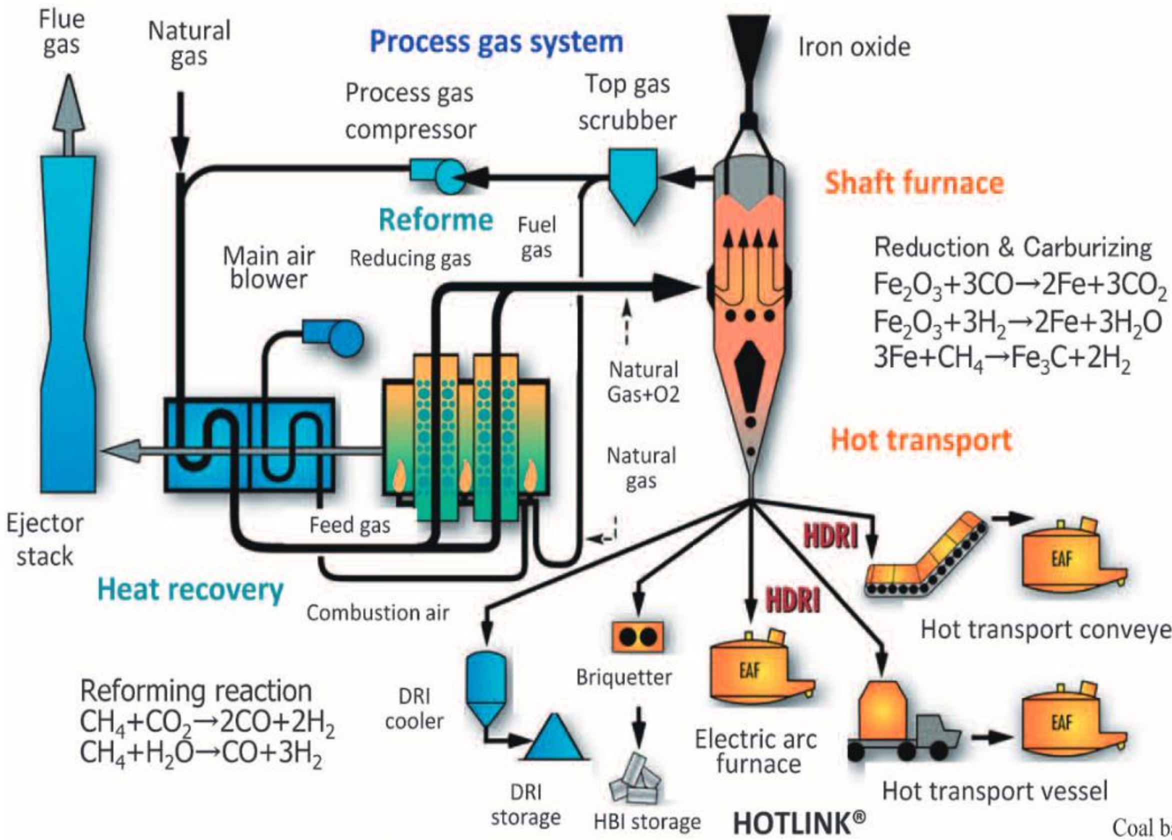

Fig. 7 MIDREX process flow sheet [8)]

Reducing takes place in solid state (~800-1050° C)

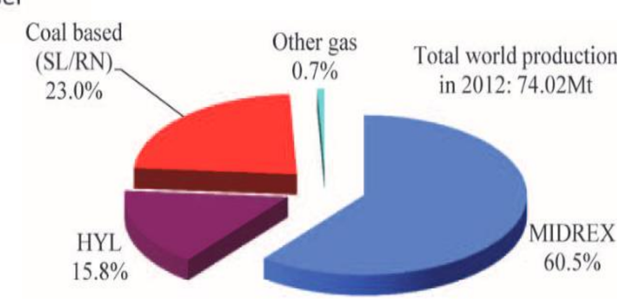

Fig. 6 World DRI production processes in 2012 [5)]

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Tanaka (2015). Resources Trend and Use of Direct Reduced Iron in Steelmaking Process

DRI USING HYDROGEN?

Direct reduced iron with pure H_2

- Hydrogen would be a good reducing agent:
  - H_2 has been shown to react more rapidly than CO → reactor size can be decreased compared to current MIDREX and HYL [1]

- ….but price and availability are a challenge

- Using pure H_2 is more or less in development phase still
  - Few different processes/approaches
    - Circored (Outotec's dual fluid bed process, H_2 from natural gas, "commercial")
    - Hydrogen Flash Ironmaking (University of Utah, fundamental research [2])
    - **H_2 in shaft kiln ("H_2 Midrex")**

[1] da Costa et al (2014). Modelling a new low CO2 emissions hydrogen steelmaking process

[2] Sohn&Mosabbad (2016). Development of a Novel Flash Ironmaking Technology with Greatly Reduced Energy Consumption and CO2 Emissions

H_2 DRI

THEORETICAL CASE STUDY BASED ON LITERATURE SOURCES

Case description

- **H_2 DRI case**: investment into an electrolytic H_2-based direct reduced iron process

  Vs

- **Reference case**: refurbishment of the current process

- Mill capacity ~2.6 $Mt_{crude\ steel}$/a

Changes in:

- Electricity consumption
- Direct CO_2 emissions
- Coke and PCI coal consumption
- LNG purchase
- O_2 purchase/sales
- CAPEX

H_2 DRI case

- Electrolysers + shaft furnace H_2 direct reduction process + electric arc furnace (EAF)
- Storage of hydrogen is not considered (electrolysers assumed to be run 8600 h/a at full capacity)
- Coke gas assumed to be replaced by additional LNG in steel rolling processes and a small amount of coal is still used in the electric arc furnace
- No change in district/process heat revenues (large excess) or other OPEX

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Electricity requirement for electrolytic H_2 DRI process

	GJ/t crude steel
Hydrogen/electrolysis	11.5
DRI	0.439
EAF	2.068
Hot rolling	0.375
SUM	**14.3**

Values based on Fischedick et al. / Journal of Cleaner Production 84 (2014) 563-580, adjusted to suit to studied case, for example the lower scrap metal content

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CAPEX

	Reference case	H_2 DRI case
Blast furnace refurb.	74 €/t CS [2]	
Basic oxygen furnace refurbishment	64 €/t CS [2]	
Coke plant refurb.	17 €/t CS [2]	
TOTAL	**=155 €/t crude steel**	
DRI process		161* €/t CS [2]
Electric arc furnace		184 €/t CS [2]
Electrolysers		650 €/kW_{LHV} [1] 236 €/t CS
TOTAL		**=581 €/t crude steel**

[1] Fischedick et al. / Journal of Cleaner Production 84 (2014)
[2] Wörtler et al. (2013). Steel's Contribution to a low Carbon Europe 2050.
*process using electrolytic H_2 was assumed to cost 30% less than natural gas based MIDREX

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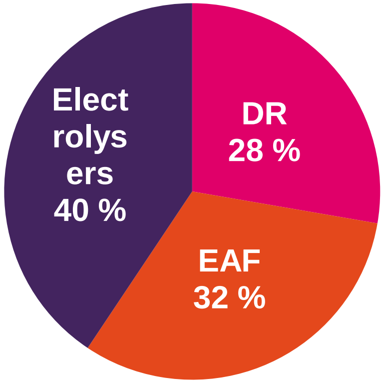

Implications of adopting H_2 DRI

- Direct **CO_2 emissions** would be **reduced by almost 90%**
- **Electricity consumption** would **increase more than 10 TWh**
- **~1 TWh more LNG** would be required for rolling
- **Over 1 Mt of oxygen** would be produced as a by-product
  - total demand in Finland is ~1.3 Mt/a.

Economics?

Excel tool

OBF w/o CCS

CO2 €/t	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80
80	-90	-87	-85	-82	-79	-76	-73	-71	-68	-65	-62	-59	-56	-54	-51	-48	-45	-42	-39	-37	-34	-31	-28	-25	-23	-20	-17	-14	-11	-8.5	-5.6	-2.8	-0	2.8	5.6	8.5
77	-86	-84	-81	-78	-75	-72	-69	-67	-64	-61	-58	-55	-53	-50	-47	-44	-41	-38	-36	-33	-30	-27	-24	-21	-19	-16	-13	-10	-7.4	-4.6	-1.7	1.1	3.9	6.7	9.5	12
74	-82	-80	-77	-74	-71	-68	-66	-63	-60	-57	-54	-51	-49	-46	-43	-40	-37	-35	-32	-29	-26	-23	-20	-18	-15	-12	-9.1	-6.3	-3.5	-0.7	2.2	5	7.8	11	13	16
71	-79	-76	-73	-70	-67	-64	-62	-59	-56	-53	-50	-48	-45	-42	-39	-36	-33	-31	-28	-25	-22	-19	-17	-14	-11	-8	-5.2	-2.4	0.4	3.2	6.1	8.9	12	15	17	20
68	-75	-72	-69	-66	-63	-61	-58	-55	-52	-49	-46	-44	-41	-38	-35	-32	-30	-27	-24	-21	-18	-15	-13	-9.8	-7	-4.1	-1.3	1.5	4.3	7.1	10	13	16	18	21	24
65	-71	-68	-65	-62	-59	-57	-54	-51	-48	-45	-43	-40	-37	-34	-31	-28	-26	-23	-20	-17	-14	-12	-8.7	-5.9	-3.1	-0.2	2.6	5.4	8.2	11	14	17	19	22	25	28
62	-67	-64	-61	-58	-56	-53	-50	-47	-44	-41	-39	-36	-33	-30	-27	-25	-22	-19	-16	-13	-10	-7.6	-4.8	-2	0.8	3.7	6.5	9.3	12	15	18	21	23	26	29	32
59	-63	-60	-57	-54	-52	-49	-46	-43	-40	-38	-35	-32	-29	-26	-23	-21	-18	-15	-12	-9.4	-6.5	-3.7	-0.9	1.9	4.7	7.6	10	13	16	19	22	24	27	30	33	36
56	-59	-56	-53	-51	-48	-45	-42	-39	-36	-34	-31	-28	-25	-22	-20	-17	-14	-11	-8.3	-5.5	-2.6	0.2	3	5.8	8.6	11	14	17	20	23	26	28	31	34	37	40
53	-55	-52	-50	-47	-44	-41	-38	-35	-33	-30	-27	-24	-21	-18	-16	-13	-10	-7.2	-4.4	-1.6	1.3	4.1	6.9	9.7	13	15	18	21	24	27	29	32	35	38	41	44
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47	-47	-45	-42	-39	-36	-33	-30	-28	-25	-22	-19	-16	-14	-11	-7.9	-5	-2.2	0.6	3.4	6.2	9.1	12	15	18	20	23	26	29	32	34	37	40	43	46	49	51
44	-43	-41	-38	-35	-32	-29	-27	-24	-21	-18	-15	-12	-9.6	-6.8	-4	-1.1	1.7	4.5	7.3	10	13	16	19	21	24	27	30	33	36	38	41	44	47	50	52	55
41	-40	-37	-34	-31	-28	-25	-23	-20	-17	-14	-11	-8.5	-5.7	-2.9	-0.1	2.8	5.6	8.4	11	14	17	20	22	25	28	31	34	37	39	42	45	48	51	54	56	59
38	-36	-33	-30	-27	-24	-22	-19	-16	-13	-10	-7.4	-4.6	-1.8	1	3.8	6.7	9.5	12	15	18	21	24	26	29	32	35	38	40	43	46	49	52	55	57	60	63
35	-32	-29	-26	-23	-20	-18	-15	-12	-9.2	-6.4	-3.5	-0.7	2.1	4.9	7.7	11	13	16	19	22	25	27	30	33	36	39	42	44	47	50	53	56	58	61	64	67
32	-28	-25	-22	-19	-17	-14	-11	-8.1	-5.3	-2.5	0.4	3.2	6	8.8	12	14	17	20	23	26	29	31	34	37	40	43	45	48	51	54	57	60	62	65	68	71
29	-24	-21	-18	-15	-13	-9.8	-7	-4.2	-1.4	1.4	4.3	7.1	9.9	13	16	18	21	24	27	30	32	35	38	41	44	47	49	52	55	58	61	63	66	69	72	75
26	-20	-17	-14	-12	-8.8	-5.9	-3.1	-0.3	2.5	5.3	8.2	11	14	17	19	22	25	28	31	34	36	39	42	45	48	50	53	56	59	62	65	67	70	73	76	79
23	-16	-13	-11	-7.7	-4.9	-2	0.8	3.6	6.4	9.2	12	15	18	21	23	26	29	32	35	37	40	43	46	49	52	54	57	60	63	66	68	71	74	77	80	83
20	-12	-9.4	-6.6	-3.8	-1	1.9	4.7	7.5	10	13	16	19	22	24	27	30	33	36	39	41	44	47	50	53	55	58	61	64	67	70	72	75	78	81	84	86
17	-8	-5.5	-2.7	0.1	2.9	5.8	8.6	11	14	17	20	23	25	28	31	34	37	40	42	45	48	51	54	57	59	62	65	68	71	73	76	79	82	85	88	90
14	-4	-1.6	1.2	4	6.8	9.7	12	15	18	21	24	27	29	32	35	38	41	43	46	49	52	55	58	60	63	66	69	72	75	77	80	83	86	89	91	94
11	-1	2.3	5.1	7.9	11	14	16	19	22	25	28	30	33	36	39	42	45	47	50	53	56	59	61	64	67	70	73	76	78	81	84	87	90	93	95	98
8	3	6.2	9	12	15	17	20	23	26	29	32	34	37	40	43	46	48	51	54	57	60	63	65	68	71	74	77	79	82	85	88	91	94	96	99	102
5	7	10	13	16	19	21	24	27	30	33	35	38	41	44	47	50	52	55	58	61	64	66	69	72	75	78	81	83	86	89	92	95	97	100	103	106

Electricity (incl. transmission and net taxes), €/MWh

- Profitability maps vs. reference case are shown for the studied case
- Sliders for sensitivity analysis

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LNG price	40	€/MWh
Coal price (PCI)	12	€/MWh
Coke price/value	150	€/t
Biocoke price	40	€/MWh
C-neutral MeOH value	76	€/MWh
WACC	11	%
Economic timeframe	16	years
Investment sensitivity	4	%
CO2 transp.&storage cost	40	€/t
HKA	8600	h/a
Share of biocoke	50	% of PCI (enb.)
Value of oxygen	70	€/t
Value of surplus oxygen	2	€/t

Default market prices/values

	Value	Unit
LNG	42	€/MWh
Coal (for PCI or EAF)	12	€/MWh
Coke	150	€/t
Value of excess oxygen	10*	€/t

*low average price as it is not reasonable to assume that all of the oxygen could be sold

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WACC 8%, timeframe 20 years

Additional cost (M€/a) compared to reference case

Default values

H2 DRI + EAF (M€/a)

10 €/MWh — 25 €/MWh

80 €/t — 35 €/t

CO2 €/t	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80
80	-164	-141	-119	-97	-75	-52	-30	-7.6	15	37	59	82	104	126	148	171	193	215	238	260	282	305	327	349	371	394	416	438	461	483	505	527	550	572	594	617
77	-153	-131	-109	-86	-64	-42	-19	2.9	25	47	70	92	114	137	159	181	204	226	248	270	293	315	337	360	382	404	426	449	471	493	516	538	560	583	605	627
74	-143	-120	-98	-76	-54	-31	-9	13	36	58	80	103	125	147	169	192	214	236	259	281	303	325	348	370	392	415	437	459	482	504	526	548	571	593	615	638
71	-132	-110	-88	-65	-43	-21	1.5	24	46	68	91	113	135	158	180	202	224	247	269	291	314	336	358	381	403	425	447	470	492	514	537	559	581	604	626	648
68	-122	-99	-77	-55	-33	-10	12	34	57	79	101	124	146	168	190	213	235	257	280	302	324	346	369	391	413	436	458	480	503	525	547	569	592	614	636	659
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62	-101	-78	-56	-34	-12	11	33	55	78	100	122	144	167	189	211	234	256	278	301	323	345	367	390	412	434	457	479	501	524	546	568	590	613	635	657	680
59	-90	-68	-46	-23	-1.1	21	43	66	88	110	133	155	177	200	222	244	266	289	311	333	356	378	400	423	445	467	489	512	534	556	579	601	623	645	668	690
56	-80	-58	-35	-13	9.4	32	54	76	99	121	143	165	188	210	232	255	277	299	322	344	366	388	411	433	455	478	500	522	544	567	589	611	634	656	678	701
53	-69	-47	-25	-2.4	20	42	64	87	109	131	154	176	198	221	243	265	287	310	332	354	377	399	421	443	466	488	510	533	555	577	600	622	644	666	689	711
50	-59	-37	-14	8.1	30	53	75	97	120	142	164	186	209	231	253	276	298	320	343	365	387	409	432	454	476	499	521	543	565	588	610	632	655	677	699	722
47	-48	-26	-3.7	19	41	63	85	108	130	152	175	197	219	242	264	286	308	331	353	375	398	420	442	464	487	509	531	554	576	598	621	643	665	687	710	732
44	-38	-16	6.7	29	51	74	96	118	141	163	185	207	230	252	274	297	319	341	363	386	408	430	453	475	497	520	542	564	586	609	631	653	676	698	720	743
41	-27	-5.1	17	40	62	84	106	129	151	173	196	218	240	262	285	307	329	352	374	396	419	441	463	485	508	530	552	575	597	619	642	664	686	708	731	753
38	-17	5.4	28	50	72	95	117	139	161	184	206	228	251	273	295	318	340	362	384	407	429	451	474	496	518	541	563	585	607	630	652	674	697	719	741	763
35	-6	16	38	61	83	105	127	150	172	194	217	239	261	283	306	328	350	373	395	417	440	462	484	506	529	551	573	596	618	640	663	685	707	729	752	774
32	4	26	49	71	93	116	138	160	182	205	227	249	272	294	316	339	361	383	405	428	450	472	495	517	539	562	584	606	628	651	673	695	718	740	762	784
29	15	37	59	81	104	126	148	171	193	215	238	260	282	304	327	349	371	394	416	438	461	483	505	527	550	572	594	617	639	661	683	706	728	750	773	795
26	25	47	70	92	114	137	159	181	203	226	248	270	293	315	337	360	382	404	426	449	471	493	516	538	560	582	605	627	649	672	694	716	739	761	783	805
23	36	58	80	102	125	147	169	192	214	236	259	281	303	325	348	370	392	415	437	459	481	504	526	548	571	593	615	638	660	682	704	727	749	771	794	816
20	46	68	91	113	135	158	180	202	224	247	269	291	314	336	358	380	403	425	447	470	492	514	537	559	581	603	626	648	670	693	715	737	760	782	804	826
17	57	79	101	123	146	168	190	213	235	257	280	302	324	346	369	391	413	436	458	480	502	525	547	569	592	614	636	659	681	703	725	748	770	792	815	837
14	67	89	112	134	156	179	201	223	245	268	290	312	335	357	379	401	424	446	468	491	513	535	558	580	602	624	647	669	691	714	736	758	781	803	825	847
11	78	100	122	144	167	189	211	234	256	278	300	323	345	367	390	412	434	457	479	501	523	546	568	590	613	635	657	680	702	724	746	769	791	813	836	858
8	88	110	133	155	177	199	222	244	266	289	311	333	356	378	400	422	445	467	489	512	534	556	579	601	623	645	668	690	712	735	757	779	801	824	846	868
5	98	121	143	165	188	210	232	255	277	299	321	344	366	388	411	433	455	478	500	522	544	567	589	611	634	656	678	700	723	745	767	790	812	834	857	879

Electricity (incl. transmission and net taxes), €/MWh

Additional cost (M€/a) compared to reference case

Electrolyser CAPEX 650→300 €/kW

H2 DRI + EAF (M€/a)

10 €/MWh — 28 €/MWh

80 €/t — 23 €/t

CO2 €/t	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80
80	-201	-178	-156	-134	-111	-89	-67	-45	-22	0.[illegible]	22	45	67	89	112	134	156	178	201	223	245	268	290	312	335	357	379	401	424	446	468	491	513	535	557	580
77	-190	-168	-146	-123	-101	-79	-56	-34	-12	11	33	55	77	100	122	144	167	189	211	234	256	278	300	323	345	367	390	412	434	456	479	501	523	546	568	590
74	-180	-157	-135	-113	-90	-68	-46	-24	-1.[illegible]	21	43	66	88	110	133	155	177	199	222	244	266	289	311	333	355	378	400	422	445	467	489	512	534	556	578	601
71	-169	-147	-125	-102	-80	-58	-35	-13	9.2	32	54	76	98	121	143	165	188	210	232	254	277	299	321	344	366	388	411	433	455	477	500	522	544	567	589	611
68	-159	-136	-114	-92	-69	-47	-25	-2.[illegible]	20	42	64	87	109	131	154	176	198	220	243	265	287	310	332	354	376	399	421	443	466	488	510	533	555	577	599	622
65	-148	-126	-104	-81	-59	-37	-14	7.9	30	53	75	97	119	142	164	186	209	231	253	275	298	320	342	365	387	409	432	454	476	498	521	543	565	588	610	632
62	-138	-115	-93	-71	-48	-26	-3.[illegible]	18	41	63	85	108	130	152	174	197	219	241	264	286	308	331	353	375	397	420	442	464	487	509	531	554	576	598	620	643
59	-127	-105	-83	-60	-38	-16	6.6	29	51	73	96	118	140	163	185	207	230	252	274	296	319	341	363	386	408	430	453	475	497	519	542	564	586	609	631	653
56	-117	-94	-72	-50	-28	-5.[illegible]	17	39	62	84	106	129	151	173	195	218	240	262	285	307	329	352	374	396	418	441	463	485	508	530	552	574	597	619	641	664
53	-106	-84	-62	-39	-17	5.3	28	50	72	94	117	139	161	184	206	228	251	273	295	317	340	362	384	407	429	451	473	496	518	540	563	585	607	630	652	674
50	-96	-73	-51	-29	-6.[illegible]	16	38	60	83	105	127	150	172	194	216	239	261	283	306	328	350	373	395	417	439	462	484	506	529	551	573	595	618	640	662	685
47	-85	-63	-41	-18	4	26	49	71	93	115	138	160	182	205	227	249	272	294	316	338	361	383	405	428	450	472	494	517	539	561	584	606	628	651	673	695
44	-75	-52	-30	-7.[illegible]	14	37	59	81	104	126	148	171	193	215	237	260	282	304	327	349	371	393	416	438	460	483	505	527	550	572	594	616	639	661	683	706
41	-64	-42	-20	2.6	25	47	70	92	114	136	159	181	203	226	248	270	292	315	337	359	382	404	426	449	471	493	515	538	560	582	605	627	649	672	694	716
38	-54	-31	-9.[illegible]	13	35	58	80	102	125	147	169	191	214	236	258	281	303	325	348	370	392	414	437	459	481	504	526	548	571	593	615	637	660	682	704	727
35	-43	-21	1.3	24	46	68	91	113	135	157	180	202	224	247	269	291	313	336	358	380	403	425	447	470	492	514	536	559	581	603	626	648	670	692	715	737
32	-33	-1[illegible]	12	34	56	79	101	123	146	168	190	212	235	257	279	302	324	346	369	391	413	435	458	480	502	525	547	569	592	614	636	658	681	703	725	748
29	-22	-0	22	45	67	89	111	134	156	178	201	223	245	268	290	312	334	357	379	401	424	446	468	491	513	535	557	580	602	624	647	669	691	713	736	758
26	-1[illegible]	10	33	55	77	100	122	144	167	189	211	233	256	278	300	323	345	367	390	412	434	456	479	501	523	546	568	590	612	635	657	679	702	724	746	769
23	-1	21	43	66	88	110	132	155	177	199	222	244	266	289	311	333	355	378	400	422	445	467	489	511	534	556	578	601	623	645	668	690	712	734	757	779
20	9	31	54	76	98	121	143	165	188	210	232	254	277	299	321	344	366	388	410	433	455	477	500	522	544	567	589	611	633	656	678	700	723	745	767	790
17	20	42	64	87	109	131	153	176	198	220	243	265	287	310	332	354	376	399	421	443	466	488	510	532	555	577	599	622	644	666	689	711	733	755	778	800
14	30	52	75	97	119	142	164	186	209	231	253	275	298	320	342	365	387	409	431	454	476	498	521	543	565	588	610	632	654	677	699	721	744	766	788	811
11	41	63	85	108	130	152	174	197	219	241	264	286	308	330	353	375	397	420	442	464	487	509	531	553	576	598	620	643	665	687	710	732	754	776	799	821
8	51	73	96	118	140	163	185	207	229	252	274	296	319	341	363	386	408	430	452	475	497	519	542	564	586	609	631	653	675	698	720	742	765	787	809	831
5	62	84	106	128	151	173	195	218	240	262	285	307	329	351	374	396	418	441	463	485	508	530	552	574	597	619	641	664	686	708	730	753	775	797	820	842

Electricity (incl. transmission and net taxes), €/MWh

Additional cost (M€/a) compared to reference case

Electrolyser CAPEX 650→300 €/kW & Greenfield BF+BOF

H2 DRI + EAF (M€/a)

10 €/MWh — 35 €/MWh — 80 €/t — 5€/t

Electricity (incl. transmission and net taxes), €/MWh

CO2 €/t	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44
80	-269	-247	-225	-202	-180	-158	-135	-113	-91	-68	-46	-24	-1.5	21	43	65	88	110
77	-259	-236	-214	-192	-169	-147	-125	-103	-80	-58	-36	-13	8.9	31	54	76	98	120
74	-248	-226	-204	-181	-159	-137	-114	-92	-70	-47	-25	-2.9	19	42	64	86	109	131
71	-238	-215	-193	-171	-148	-126	-104	-82	-59	-37	-15	7.6	30	52	75	97	119	141
68	-227	-205	-183	-160	-138	-116	-93	-71	-49	-26	-4.2	18	40	63	85	107	130	152
65	-217	-194	-172	-150	-127	-105	-83	-61	-38	-16	6.3	29	51	73	95	118	140	162
62	-206	-184	-162	-139	-117	-95	-72	-50	-28	-5.5	17	39	61	84	106	128	151	173
59	-196	-173	-151	-129	-107	-84	-62	-40	-17	5	27	50	72	94	116	139	161	183
56	-185	-163	-141	-118	-96	-74	-51	-29	-6.8	15	38	60	82	105	127	149	172	194
53	-175	-152	-130	-108	-86	-63	-41	-19	3.7	26	48	71	93	115	137	160	182	204
50	-164	-142	-120	-97	-75	-53	-30	-8.1	14	36	59	81	103	126	148	170	193	215
47	-154	-131	-109	-87	-65	-42	-20	2.3	25	47	69	92	114	136	158	181	203	225
44	-143	-121	-99	-76	-54	-32	-9.5	13	35	57	80	102	124	147	169	191	213	236
41	-133	-110	-88	-66	-44	-21	1	23	46	68	90	112	135	157	179	202	224	246
38	-122	-100	-78	-55	-33	-11	12	34	56	78	101	123	145	168	190	212	234	257
35	-112	-89	-67	-45	-23	-0.3	22	44	67	89	111	133	156	178	200	223	245	267
32	-101	-79	-57	-34	-12	10	32	55	77	99	122	144	166	189	211	233	255	278
29	-91	-69	-46	-24	-1.6	21	43	65	88	110	132	154	177	199	221	244	266	288
26	-80	-58	-36	-13	8.9	31	53	76	98	120	143	165	187	210	232	254	276	299
23	-70	-48	-25	-2.9	19	42	64	86	109	131	153	175	198	220	242	265	287	309
20	-59	-37	-15	7.5	30	52	74	97	119	141	164	186	208	231	253	275	297	320
17	-49	-27	-4.3	18	40	63	85	107	130	152	174	196	219	241	263	286	308	330
14	-38	-16	6.2	29	51	73	95	118	140	162	185	207	229	251	274	296	318	341
11	-28	-5.6	17	39	61	84	106	128	150	173	195	217	240	262	284	307	329	351
8	-17	4.9	27	49	72	94	116	139	161	183	206	228	250	272	295	317	339	362
5	-7	15	38	60	82	105	127	149	171	194	216	238	261	283	305	328	350	372

CO2 €/t	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80
80	132	155	177	199	221	244	266	288	311	333	355	377	400	422	444	467	489	511
77	143	165	187	210	232	254	276	299	321	343	366	388	410	433	455	477	499	522
74	153	176	198	220	242	265	287	309	332	354	376	398	421	443	465	488	510	532
71	164	186	208	231	253	275	297	320	342	364	387	409	431	454	476	498	520	543
68	174	196	219	241	263	286	308	330	353	375	397	419	442	464	486	509	531	553
65	185	207	229	252	274	296	318	341	363	385	408	430	452	475	497	519	541	564
62	195	217	240	262	284	307	329	351	374	396	418	440	463	485	507	530	552	574
59	206	228	250	273	295	317	339	362	384	406	429	451	473	495	518	540	562	585
56	216	238	261	283	305	328	350	372	395	417	439	461	484	506	528	551	573	595
53	227	249	271	294	316	338	360	383	405	427	450	472	494	516	539	561	583	606
50	237	259	282	304	326	349	371	393	415	438	460	482	505	527	549	572	594	616
47	248	270	292	314	337	359	381	404	426	448	471	493	515	537	560	582	604	627
44	258	280	303	325	347	370	392	414	436	459	481	503	526	548	570	593	615	637
41	269	291	313	335	358	380	402	425	447	469	492	514	536	558	581	603	625	648
38	279	301	324	346	368	391	413	435	457	480	502	524	547	569	591	614	636	658
35	290	312	334	356	379	401	423	446	468	490	513	535	557	579	602	624	646	669
32	300	322	345	367	389	412	434	456	478	501	523	545	568	590	612	634	657	679
29	311	333	355	377	400	422	444	467	489	511	533	556	578	600	623	645	667	690
26	321	343	366	388	410	432	455	477	499	522	544	566	589	611	633	655	678	700
23	332	354	376	398	421	443	465	488	510	532	554	577	599	621	644	666	688	711
20	342	364	387	409	431	453	476	498	520	543	565	587	610	632	654	676	699	721
17	352	375	397	419	442	464	486	509	531	553	575	598	620	642	665	687	709	732
14	363	385	408	430	452	474	497	519	541	564	586	608	631	653	675	697	720	742
11	373	396	418	440	463	485	507	530	552	574	596	619	641	663	686	708	730	752
8	384	406	429	451	473	495	518	540	562	585	607	629	651	674	696	718	741	763
5	394	417	439	461	484	506	528	551	573	595	617	640	662	684	707	729	751	773

Conclusions & next steps

- DRI w/ electrolytic H_2 could enable basically CO_2-free steel production

- Process seems technically feasible but economics seem a bit challenging
  - But as CCS still faces a lot of opposition and obstacles, H_2 route might still be the way to go

NEO CARBON ENERGY

THANKS!