processes

Supplementary Materials:

Low-Temperature Steam Reforming of Natural Gas after LPG-Enrichment with MFI Membranes

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Table S1. Composition of the reaction gas mixtures comprising single alkanes or natural gas alkanes in 75% inert gas.

S/C	Alkane	Alkane (vol%)	Steam (vol%)
1	CH_4	12.5	12.5
2.5	CH_4	7.81	17.9
4	CH_4	5.00	20.0
1	C_2H_6	8.33	16.67
2.5	C_2H_6	4.17	20.83
4	C_2H_6	2.78	22.22
1	C_3H_8	6.25	18.75
2.5	C_3H_8	2.94	22.06
4	C_3H_8	1.92	23.08
1	*i* or *n*-C_4H_{10}	5.00	20.0
2.5	*i* or *n*-C_4H_{10}	2.27	22.73
4	*i* or *n*-C_4H_{10}	1.47	23.53
1	raw gas	8.69	16.31
2.5	raw gas	4.39	20.61
4	raw gas	2.94	22.06
1	permeate gas	6.81	18.19
2.5	permeate gas	3.26	21.74
4	permeate gas	2.14	22.86

Table S2. Composition of the reaction gas mixtures comprising binary in 75% inert gas.

S/C	CH_4 . Alkane.	CH_4 (vol%)	Alkane (vol%)	Steam (vol%)
1	CH_4 : C_2H_6 (29.6 : 70.4)	2.74	6.51	15.75
2.5	CH_4 : C_2H_6 (29.6 : 70.4)	1.41	3.35	20.24
4	CH_4 : C_2H_6 (29.6 : 70.4)	0.95	2.25	21.8
1	CH_4 : C_2H_6 (86.4 : 13.6)	10.1	1.59	13.31
2.5	CH_4 : C_2H_6 (86.4 : 13.6)	5.63	0.89	18.48
4	CH_4 : C_2H_6 (86.4 : 13.6)	3.90	0.61	20.49
1	CH_4 : C_3H_8 (29.6 : 70.4)	2.17	5.16	17.67
2.5	CH_4 : C_3H_8 (29.6 : 70.4)	1.05	2.51	21.44
4	CH_4 : C_3H_8 (29.6 : 70.4)	0.70	1.66	22.64
1	CH_4 : C_3H_8 (86.4 : 13.6)	9.51	1.50	13.99
2.5	CH_4 : C_3H_8 (86.4 : 13.6)	5.17	0.81	19.02
4	CH_4 : C_3H_8 (86.4 : 13.6)	3.55	0.56	20.89
1	CH_4 : *n*-C_4H_{10} (29.6 : 70.4)	1.80	4.30	18.9
2.5	CH_4 : *n*-C_4H_{10} (29.6 : 70.4)	0.84	2.00	22.16
4	CH_4 : *n*-C_4H_{10} (29.6 : 70.4)	0.55	1.31	23.14
1	CH_4 : *n*-C_4H_{10} (86.4 : 13.6)	8.97	1.41	14.62
2.5	CH_4 : *n*-C_4H_{10} (86.4 : 13.6)	4.78	0.75	19.47
4	CH_4 : *n*-C_4H_{10} (86.4 : 13.6)	3.25	0.51	21.24

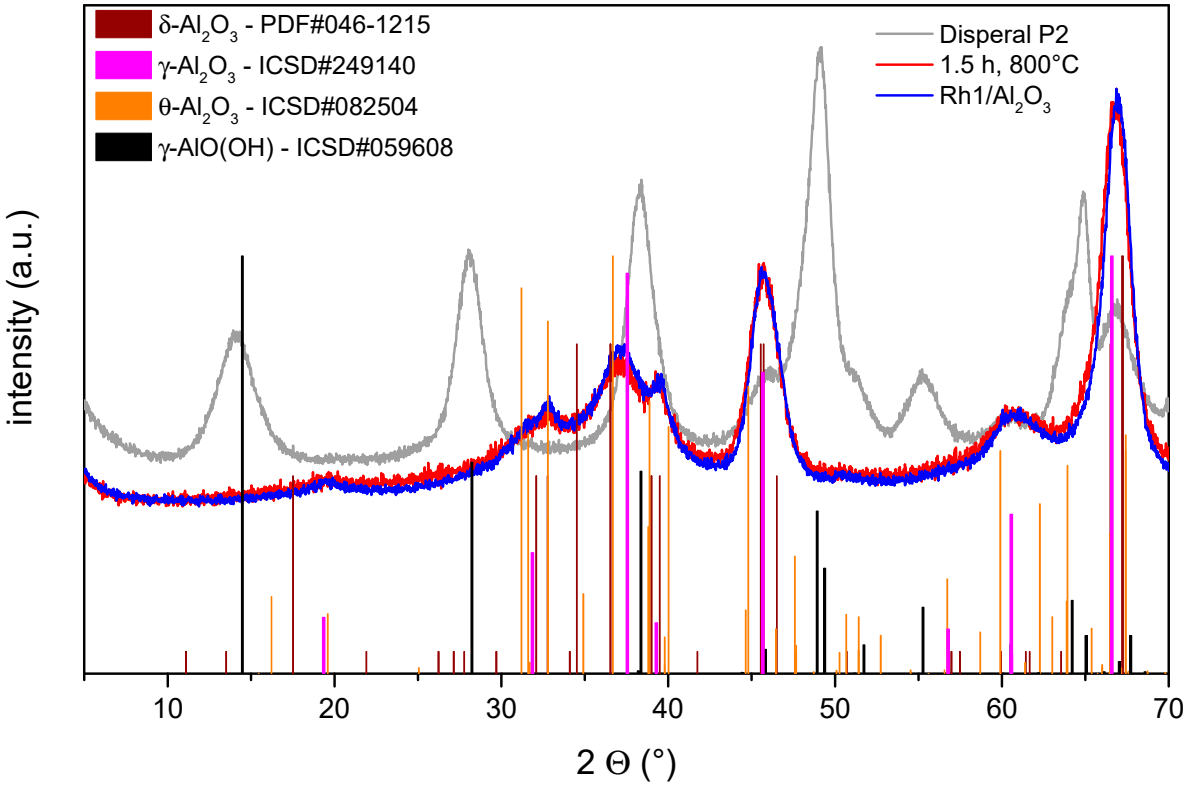
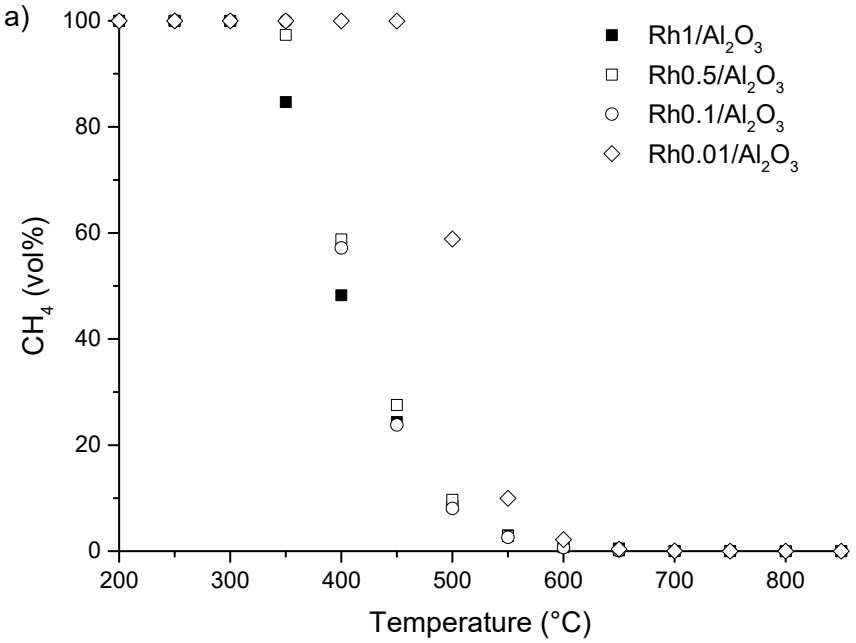
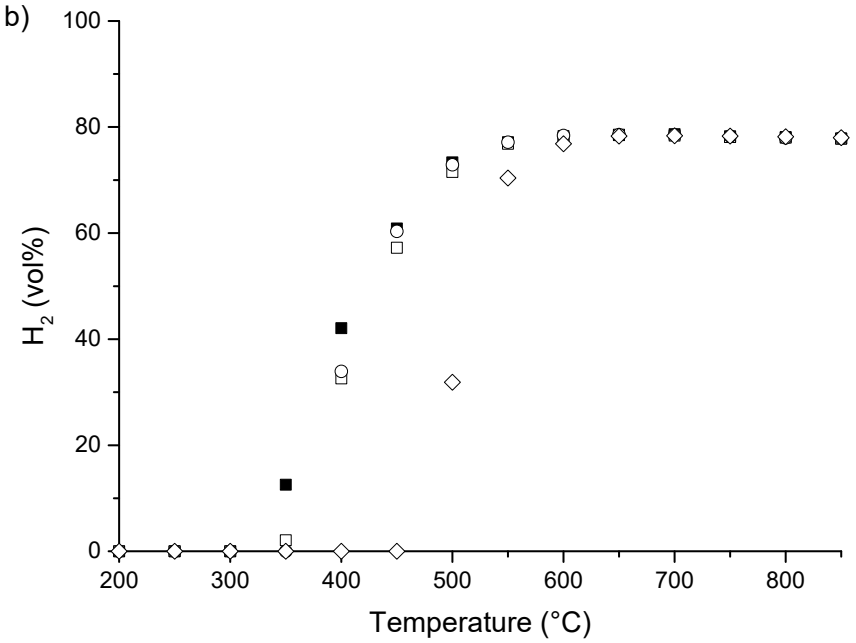


Figure S1. XRD patterns obtained from Rh1/Al2O3, the support precursor (γ–AlOOH), and the pure support (mixture of γ-, θ- and δ-alumina phases).


a)
100
80
60
40
20
0
CH_4 (vol%)
200
300
400
500
600
700
800
Temperature (°C)
$Rh1/Al_2O_3$
$Rh0.5/Al_2O_3$
$Rh0.1/Al_2O_3$
$Rh0.01/Al_2O_3$


b)
100
80
60
40
20
0
H_2 (vol%)
200
300
400
500
600
700
800
Temperature (°C)

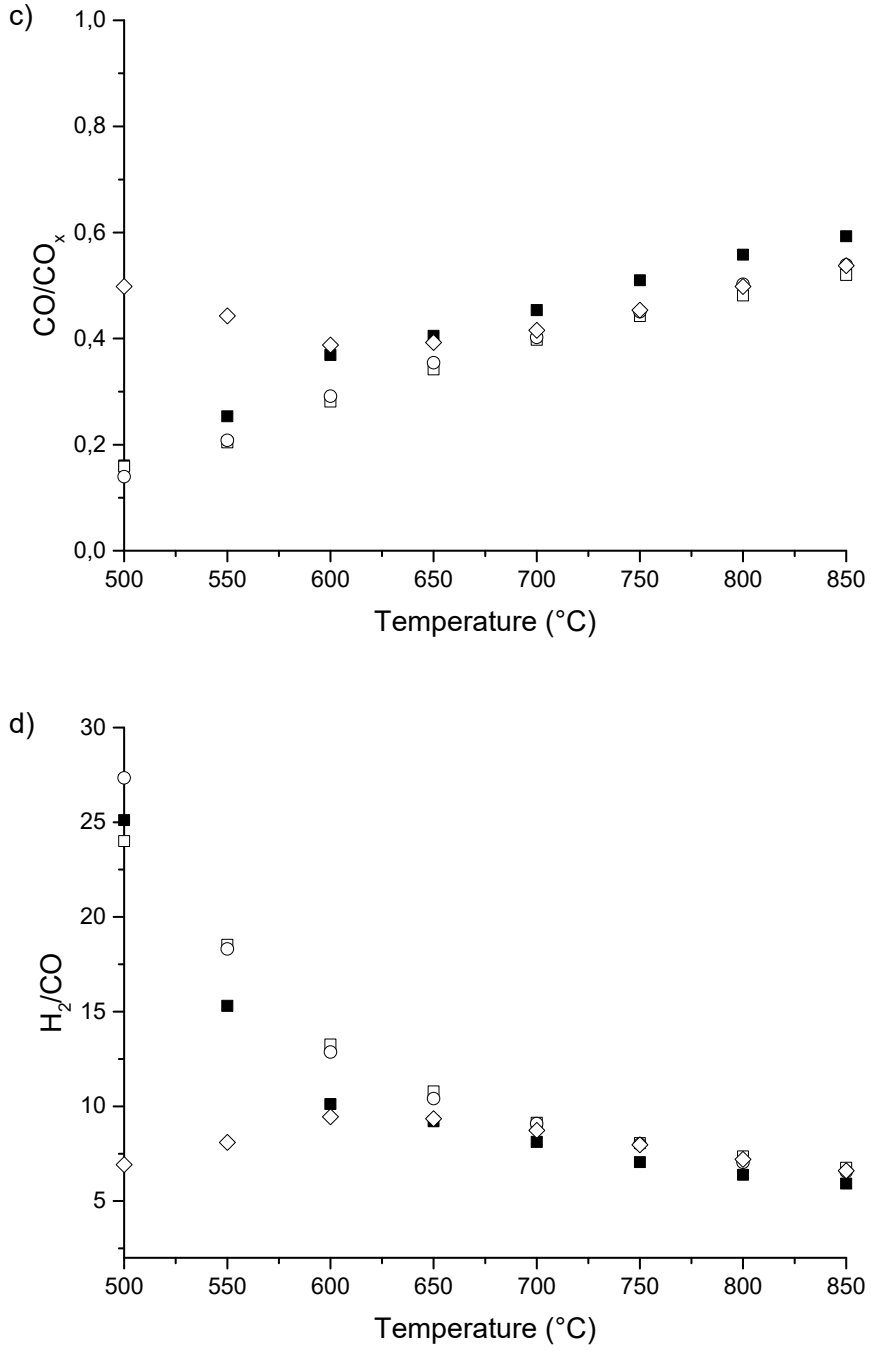
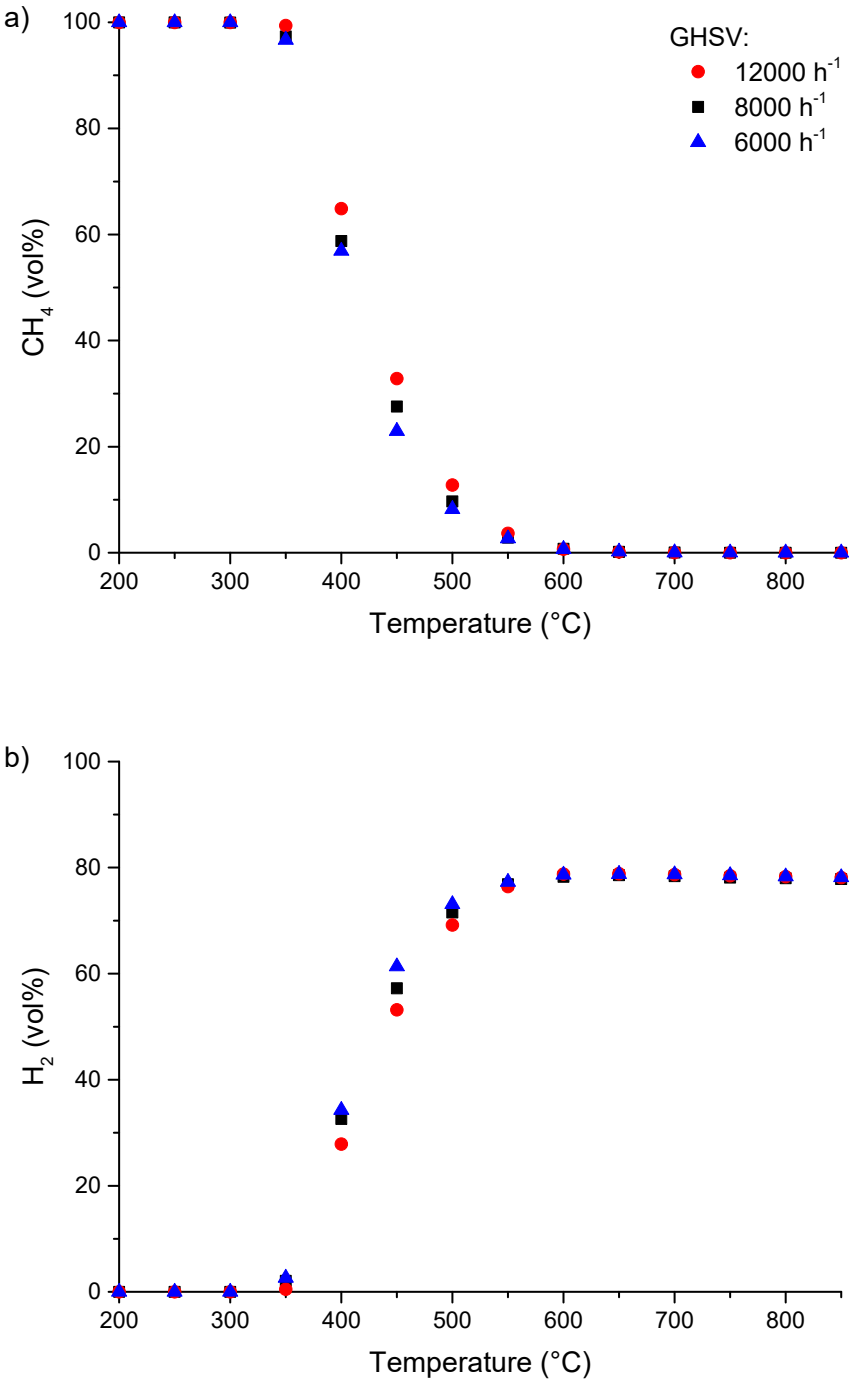


Figure S2. a) CH_4 and b) H_2 volumetric gas contents (water and inert gas excluded), c) CO/CO_x ratio, and d) H_2/CO ratio in the steam reforming of methane over Rhx/Al_2O_3 at various Rh loadings (S/C = 4).


a)
100
80
60
40
20
0
CH_4 (vol%)
200
300
400
500
600
700
800
Temperature (°C)
GHSV:
12000 h^{-1}
8000 h^{-1}
6000 h^{-1}
b)
100
80
60
40
20
0
H_2 (vol%)
200
300
400
500
600
700
800
Temperature (°C)

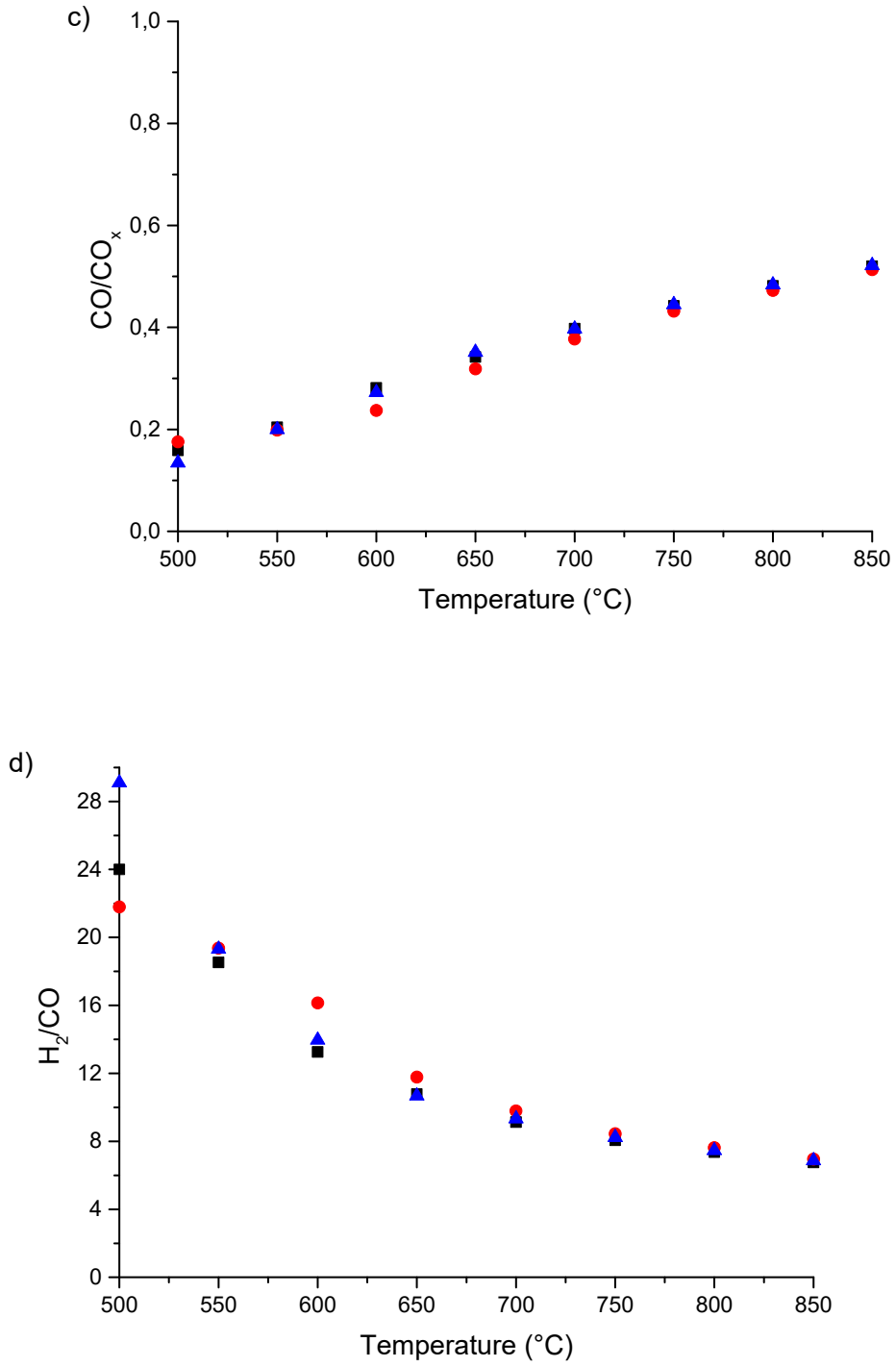
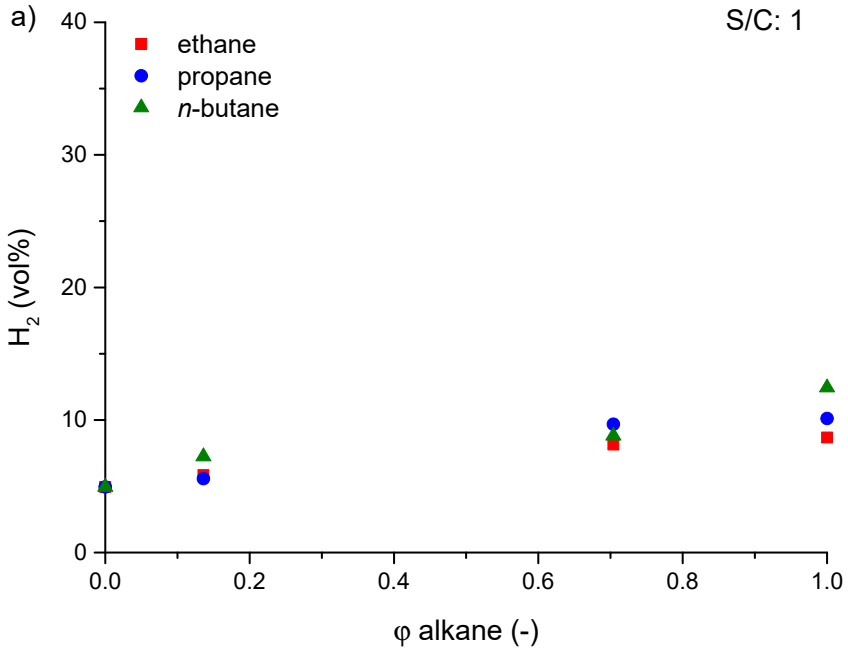
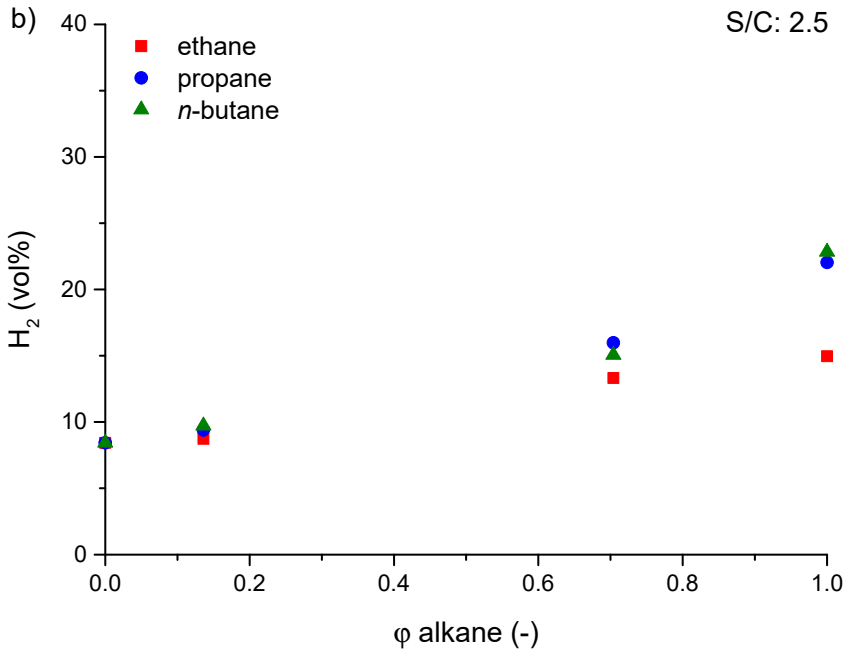


Figure S3. a) CH_4 and b) H_2 volumetric gas contents (water and inert gas excluded), c) CO/CO_x ratio, and d) H_2/CO ratio in the steam reforming of methane over $Rh_{0.5}/Al_2O_3$ at various Rh loadings at various GHSVs (S/C = 4).


a)
S/C: 1
ethane
propane
n-butane
H2 (vol%)
φ alkane (-)
0
10
20
30
40
0.0
0.2
0.4
0.6
0.8
1.0


b)
S/C: 2.5
ethane
propane
n-butane
H2 (vol%)
φ alkane (-)
0
10
20
30
40
0.0
0.2
0.4
0.6
0.8
1.0

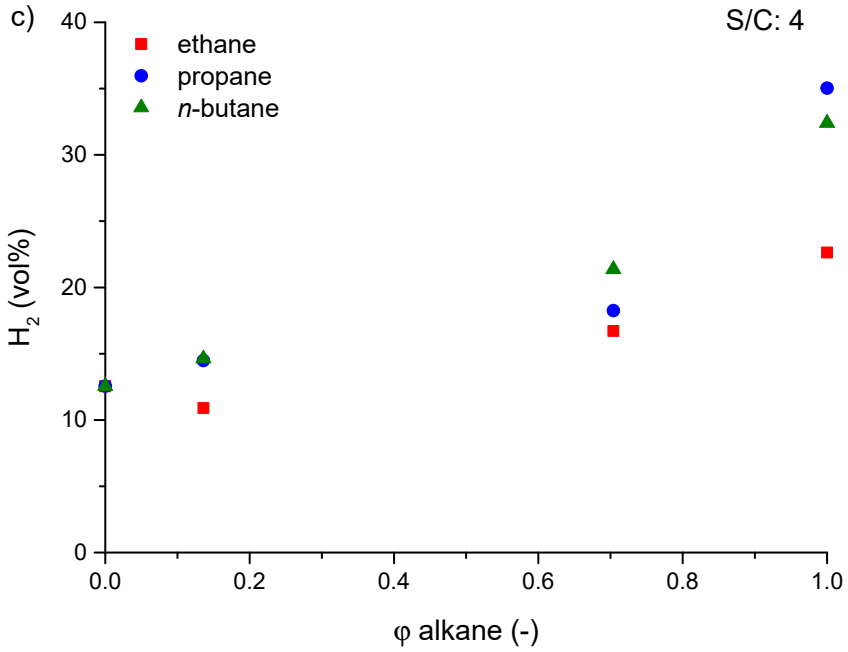
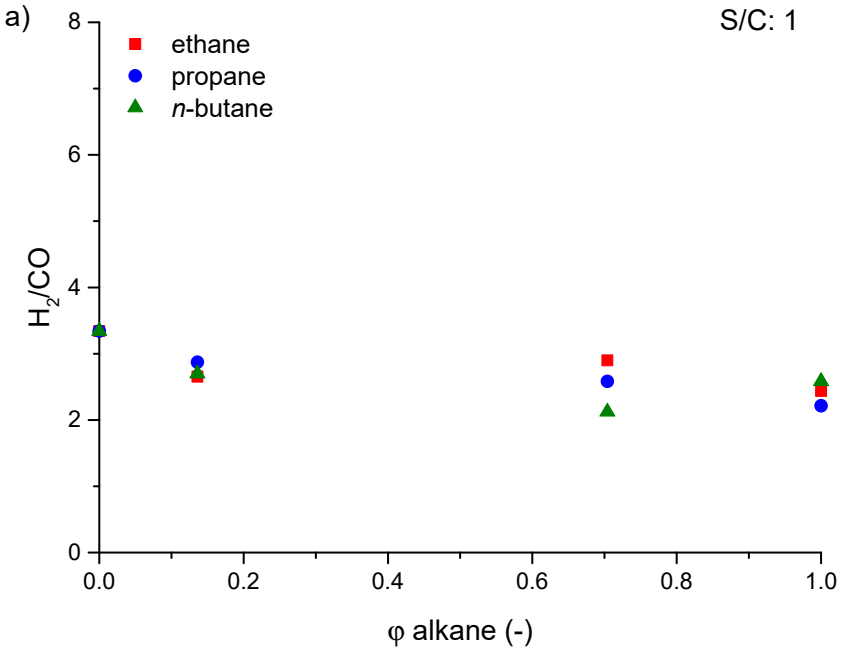
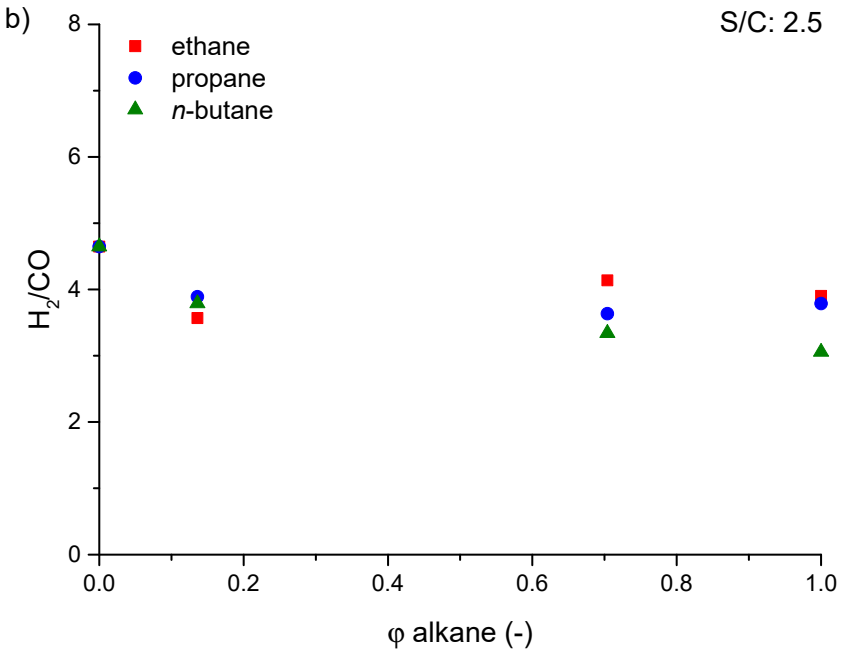


Figure S4. H_2 volumetric gas contents (water and inert gas excluded) in the steam reforming of C_2–C_4 alkanes in mixture with methane over $Rh1/Al_2O_3$ at 350 °C and S/C of a) 1, b) 2.5 and c) 4.


a)
S/C: 1
ethane
propane
n-butane
H2/CO
φ alkane (-)
0
2
4
6
8
0.0
0.2
0.4
0.6
0.8
1.0


b)
S/C: 2.5
ethane
propane
n-butane
H2/CO
φ alkane (-)
0
2
4
6
8
0.0
0.2
0.4
0.6
0.8
1.0

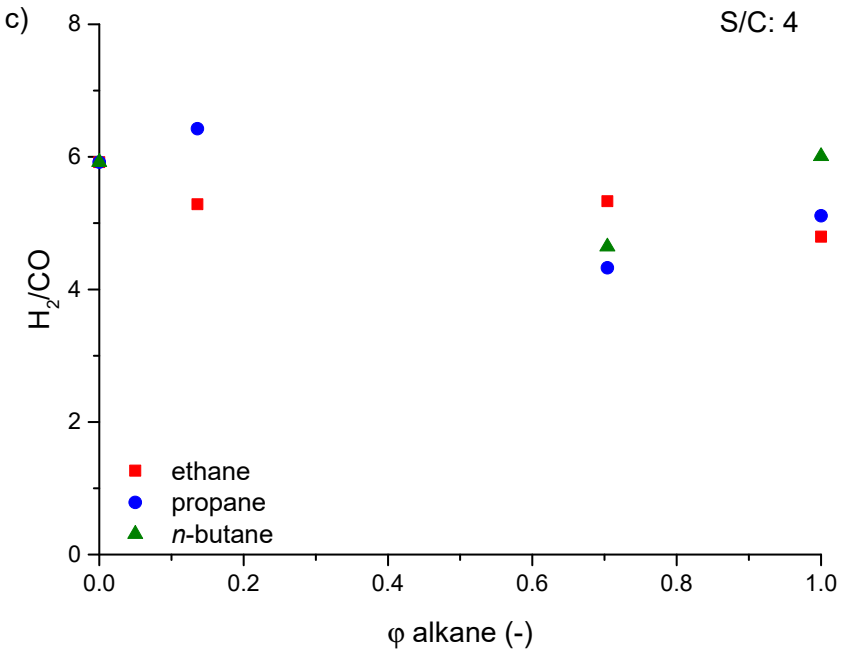


Figure S5. H_2/CO ratios in the steam reforming of C_2–C_4 alkanes in mixture with methane over Rh1/Al_2O_3 at 350 °C and S/C of a) 1, b) 2.5 and c) 4.

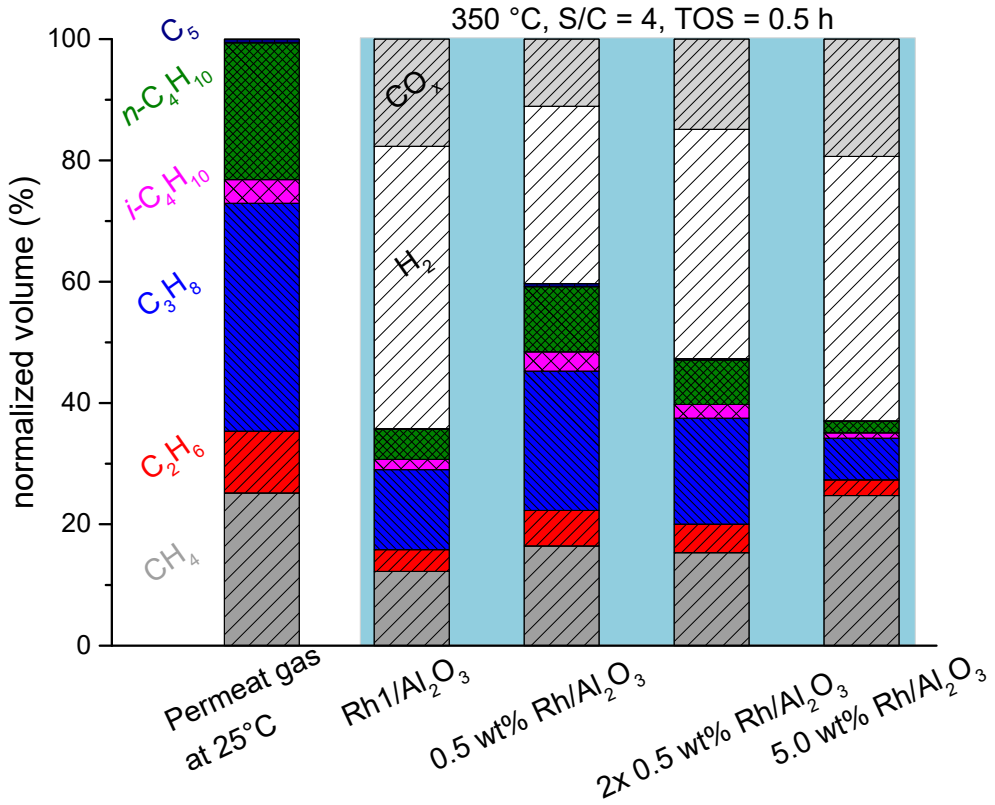
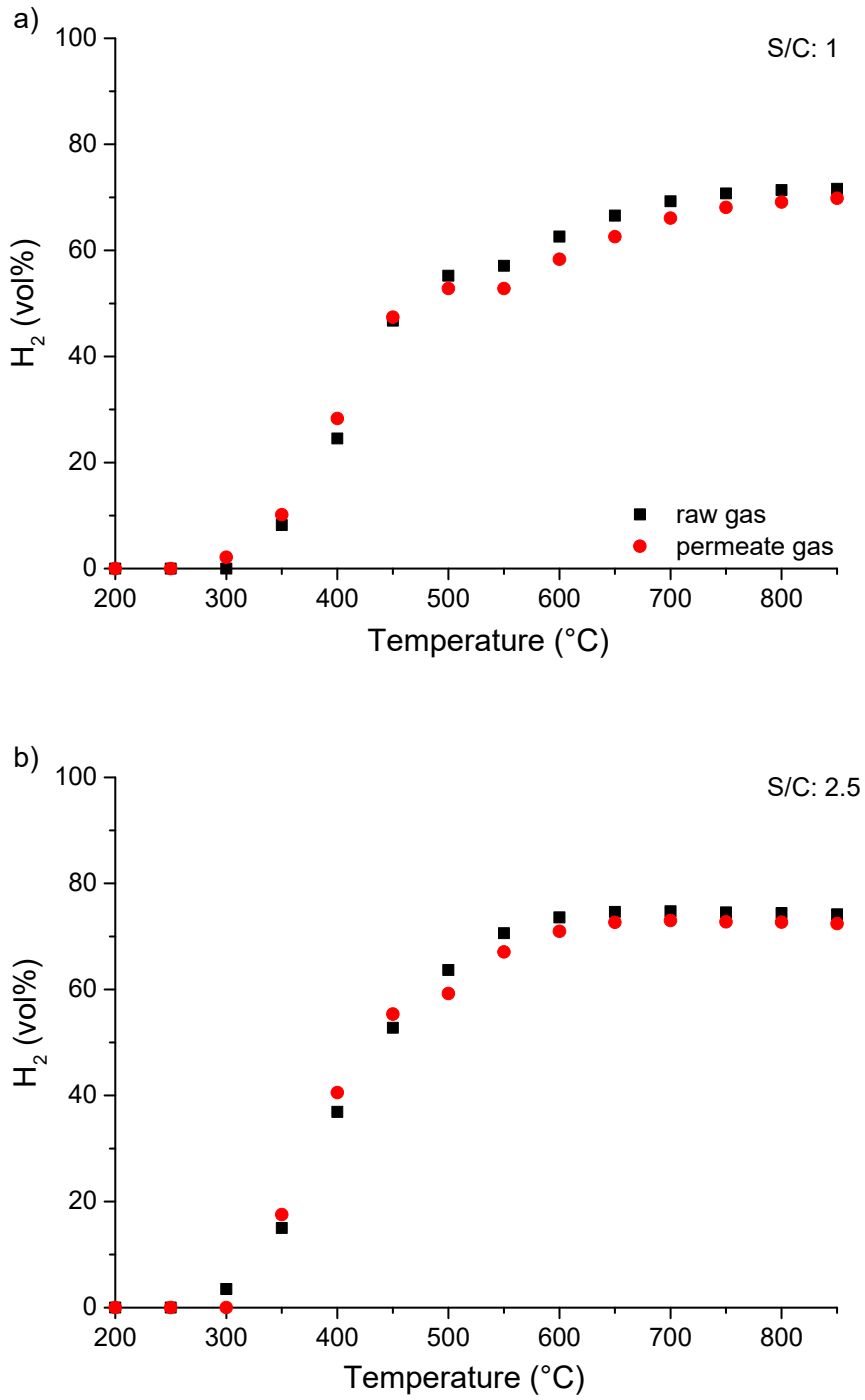


Figure S6. Volumetric gas contents of permeate gas from membrane pre-separation and after subsequent steam reforming at 350 °C and a S/C ratio of 4 over Rh1/Al_2O_3 and commercial catalysts.


a)
S/C: 1
H2 (vol%)
Temperature (°C)
raw gas
permeate gas
b)
S/C: 2.5
H2 (vol%)
Temperature (°C)

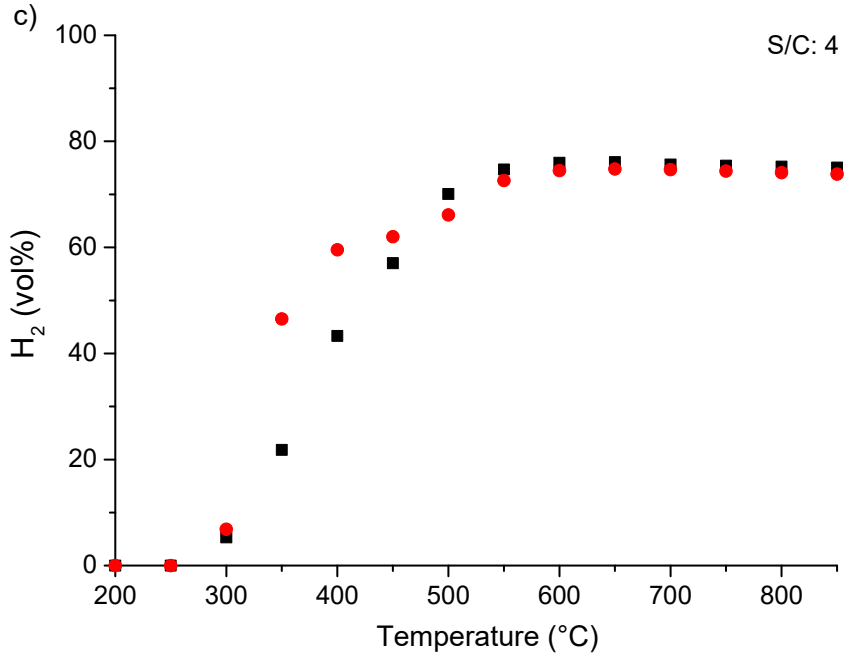
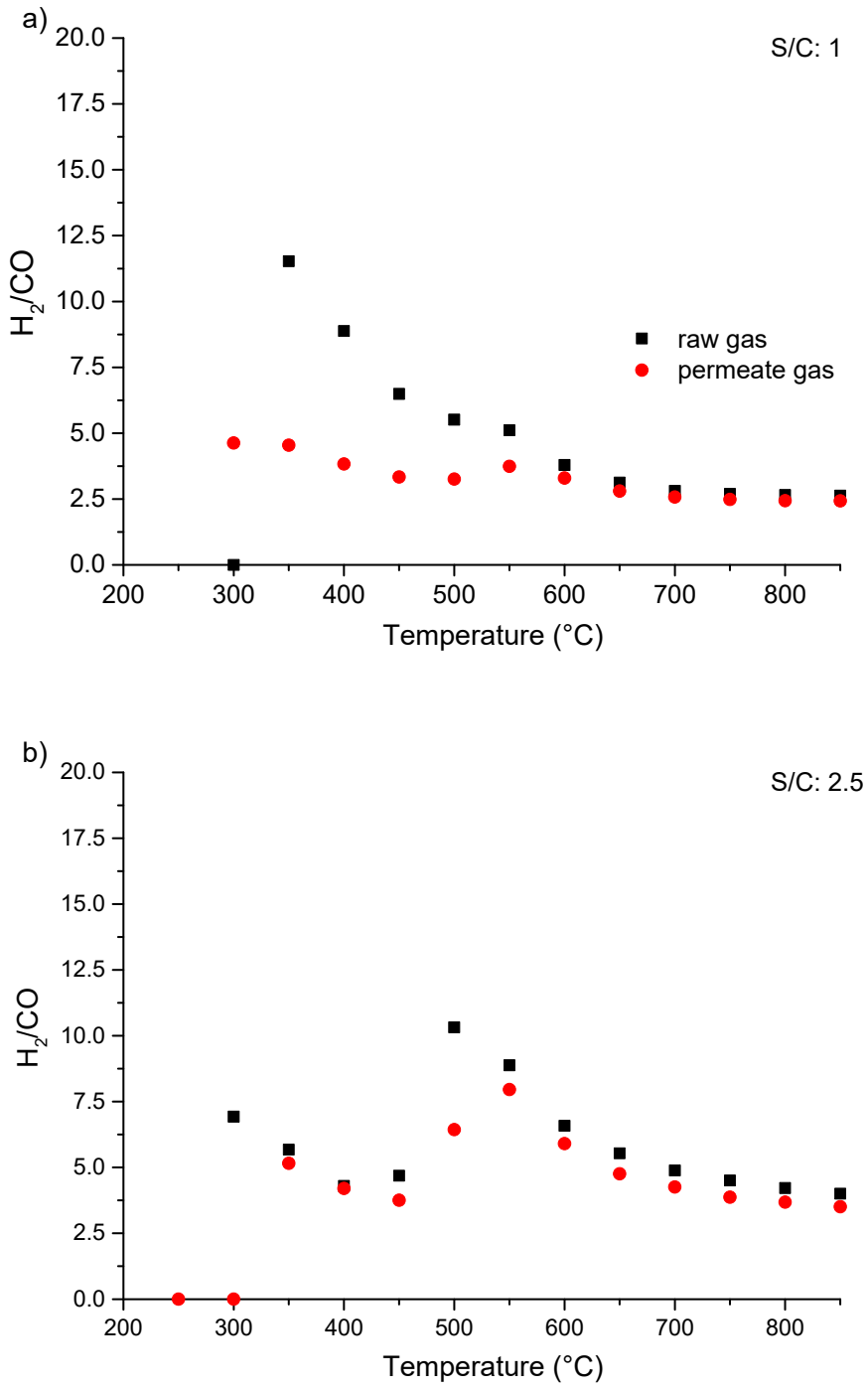


Figure S7. H_2 volumetric gas contents (water and inert gas excluded) in the steam reforming of methane over $Rh1/Al_2O_3$ at various temperatures and S/C ratios of a) 1, b) 2.5 and c) 4.


a)
S/C: 1
H_2/CO
raw gas
permeate gas
Temperature (°C)
b)
S/C: 2.5
H_2/CO
Temperature (°C)

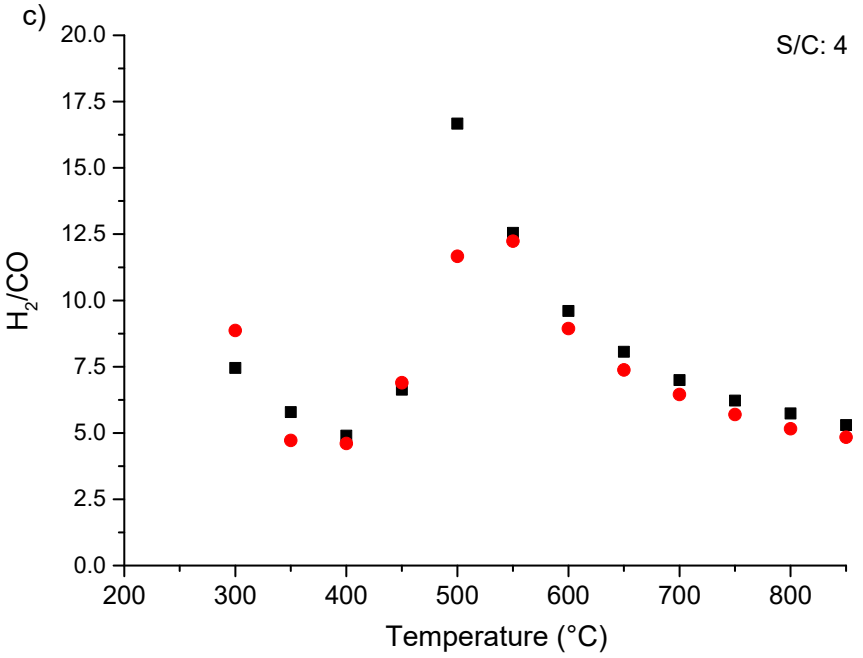
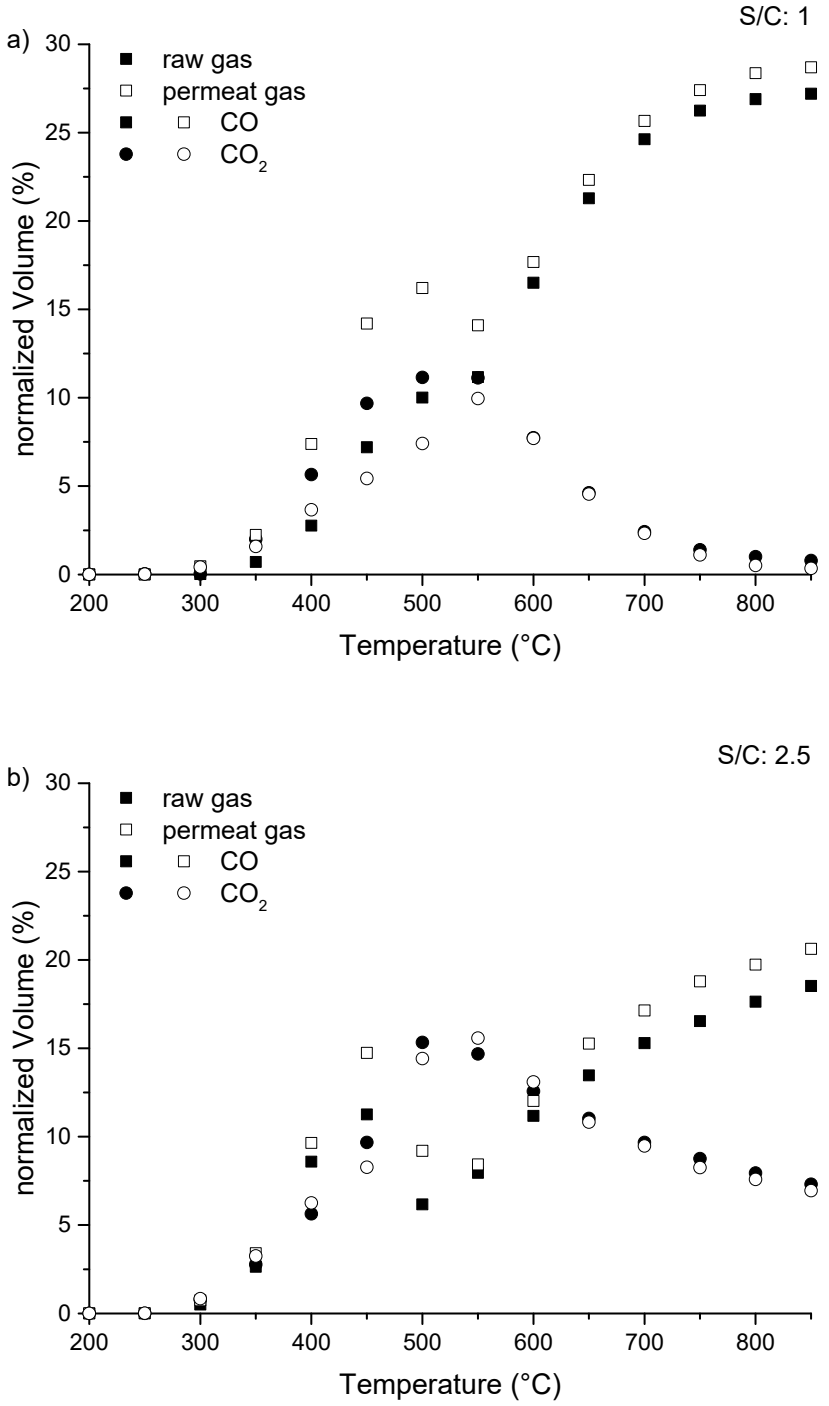


Figure S8. H_2/CO ratios in the product gases in the steam reforming of methane over Rh1/Al_2O_3 at various temperatures and S/C ratios of a) 1, b) 2.5 and c) 4.


a)
S/C: 1
raw gas
permeat gas
CO
CO2
normalized Volume (%)
Temperature (°C)
b)
S/C: 2.5
raw gas
permeat gas
CO
CO2
normalized Volume (%)
Temperature (°C)

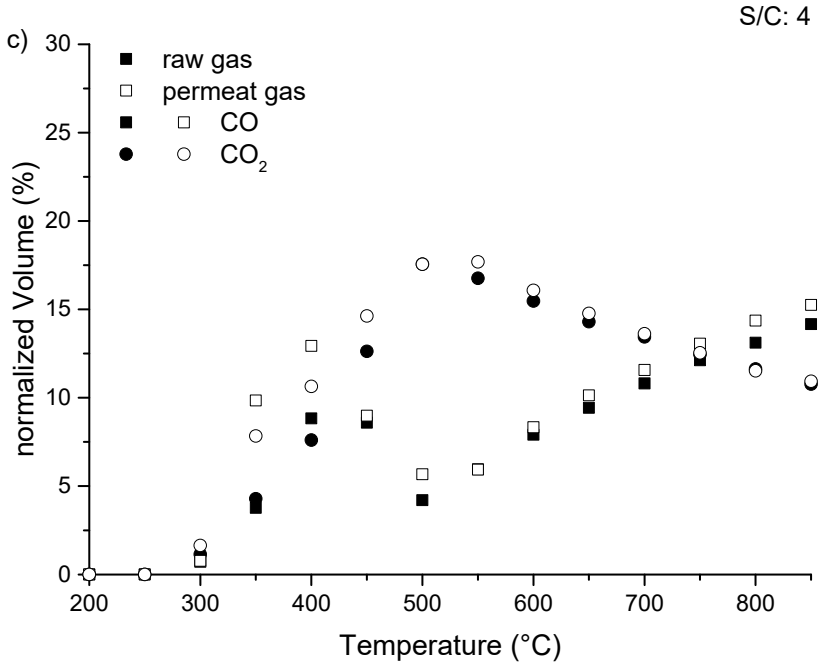


Figure S9. Volumetric CO- and CO_2-contents in the product gases (water and inert gas excluded) in the steam reforming of methane over $Rh1/Al_2O_3$ at various temperatures and S/C ratios of a) 1, b) 2.5 and c) 4.