Sustainable Chemistry for Biomass Utilization

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Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Nielsen, L. B., Tanner, D. A., & Fristrup, P. (2017). Sustainable Chemistry for Biomass Utilization. DTU Chemistry.

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Lasse Bo Nielsen
Ph.D. Thesis

27. April 2017

DTU Chemistry
Department of Chemistry

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Preface

This report is the culmination of 3 years of Ph.D. studies conducted between 2013 – 2016 at the Department of Chemistry, Technical University of Denmark and financed by the Danish Council for Independent Research, Sapere Aude. Herein, lies the results of two projects performed under supervision of Peter Fristrup. The first project is entitled “Vanadium Catalyzed Deoxydehydration With an Alcohol as Solvent and Reductant”. It is centered around a type of reactions that remove oxygen from molecules, an interesting feature for the valorization of biomass. The second project is called “Vanadium Catalyzed Reactive Distillation of Glycerol to Allyl Alcohol and Acrolein” which was aimed at the developments of a new process that converts glycerol to allyl alcohol in a reactive distillation setup catalyzed by vanadium.

Chapter 1 gives an introduction to the world energy problem and as to how biomass may become a crucial part of the solution. Chapter 2 will begin with a detailed introduction to deoxydehydration and then dive into the results obtained in the first project. Chapter 3 covers the distillation experiments in project two.

First and foremost I would like to give my gratitude to Peter Fristrup, who gave me a chance to change from computational chemistry onto a Ph.D. project centered around laboratory work. Peter has all the way through the project shown me a lot of trust and understanding, and been a great source for ideas and knowhow. David Tanner should also be acknowledged for picking up the baton and help me cross the finishing line, once Peter had left to take care of his new job.

I would also like to thank all the wonderful people in the chemistry department for their support and guidance. Special thanks go to Allan Petersen and Daniel Bo Larsen for proof reading this thesis and help me with various chemistry issues. Johannes Rytter Dethlefsen also deserve special acknowledgement for introducing me to the project and provide me with extra laboratory skills. Even though the chemistry department is full of shiny, happy people, I would like to emphasize Ana Rita Freitas Colaço, Geanna Min and Samuel Gilbert Elliot for being especially enthusiastic and joyful at all times.

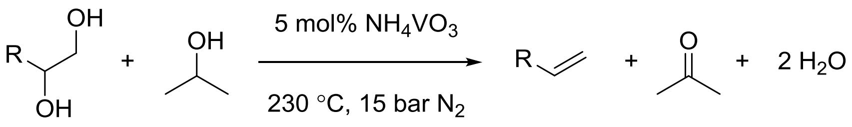
Finally I would like to thank my family and my friends outside the DTU campus, for their inexhaustible patience and support.

Abstract

Vanadium catalyzed deoxydehydration (DODH) of vicinal diols to alkenes have been investigated. The aim of the project was to examine the possibility of using an alcohol as both the solvent and the reductant. Development of a process that functions in a polar solvent was thought to be especially important, as the final goal was to use the method to convert oxygen-rich molecules from biomass into valuable compounds. Initial experiments found the DODH reaction to proceed in an autoclave at 230 °C, when 1,2-decanediol was allowed to react with 5 mol% ammonium metavanadate (NH_4VO_3) in isopropanol. After 17 hours, a yield of 1-decene that corresponded to 50 mol% of the starting substrate, could be detected using gas chromatography.

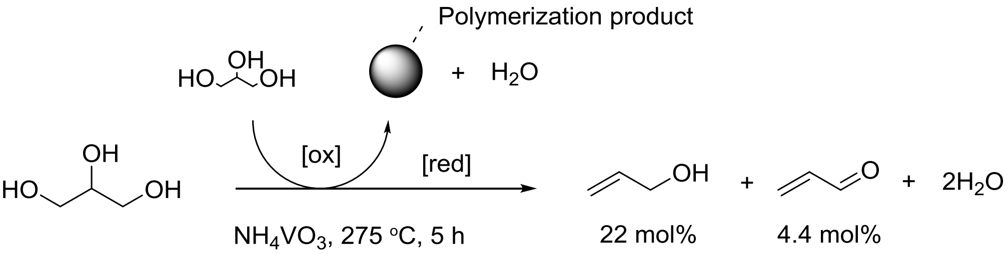
Different alcohols were tested as solvents along with their ability to reduce the vanadium center back to the oxidation state in which it is active. Secondary alcohols gave much better yields than their primary analogues and isopropanol was thus selected for further research. Catalyst optimization was carried out by comparison of the products and yields obtained when a range of different vanadium compounds were used. Most of the screened catalysts gave the same yields and product distributions, and NH_4VO_3 was judged to be a good choice based on its availability and ease of handling. Even though low turn-over numbers were found in batch experiments, the catalyst proved to be much more sustainable if reused before it gets deactivated.

Vanadium catalyzed DODH was found to have unique selectivity towards substrates containing exactly one primary and one secondary hydroxyl group. In contrast, internal diols such as 3,4-hexanediol gave no yield of alkene and both stereoisomers of 1,2-cyclohexandiol were almost completely unreactive. However, substrates that are stabilized by conjugation, such as hydrobenzoin, were found to undergo oxidative cleavage to form two aldehydes. The reactivity of the diols also depends strongly on the orientation of the hydroxyl groups relative to one another. A sharp decline in product yield was thus observed when *cis*-1,2-cyclohexanediol was added to a reaction of 1,2-hexanediol, which was in contrast to addition of the *trans* stereoisomer. A possible reason is that the *trans* isomer cannot simultaneously coordinate to the metal with both hydroxyl groups and thereby inhibit the reaction. Glycerol proved to be unreactive as well, whereas 1,2-propanediol and 3-isopropoxy-1,2-propanediol did undergo DODH to yield propene and 3-isopropoxy-1-propene, respectively.



The water that is formed as the reaction proceeds was found to inhibit the DODH so strongly that removing it might be the key to achieve alkene yields above 50 mol%. Molecular sieves, 2,2-dimethoxypropane, triethyl orthoformate and various other methods to remove water were tested and analyzed.

The vanadium catalyzed reactive distillation of glycerol has also been developed. The reaction setup and conditions were optimized to ensure a quick separation of the products from the mixture. Only 1 mol% NH_4VO_3 was enough to achieve total conversion of 23 g of glycerol, with direct collection of a mixture containing allyl alcohol, acrolein and water. The best results were obtained at 275 °C, with yields of 22 mol% allyl alcohol and roughly 4 mol% acrolein obtained after 5 hours. A black material remained in the reaction flask and its composition was determined by elemental analysis. This material was later proposed to be a polymer mainly built from acrolein and possibly also allyl alcohol and glycerol monomers. The catalytic performance of $MeReO_3$, $(NH_4)_6Mo_7O_{24}•4H_2O$ and NH_4VO_3 was compared and vanadium found to give more allyl alcohol than rhenium, which is surprising due to the increased DODH reactivity of the latter.

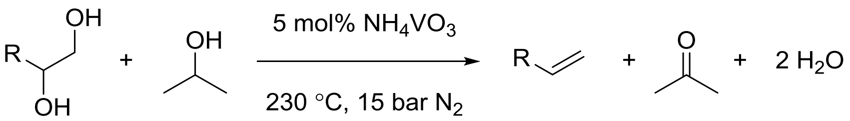


Resumé

Vanadium katalyseret deoxydehydrering (DODH) af vicinale dioler til alkener er blevet undersøgt. Projektets mål var at udforske mulighederne i at anvende en alkohol som både opløsningsmiddel og reduktant. Udvikling af en proces der virker i et polært solvent, blev anset for værende interessant eftersom målet med metoden er at anvende den til at omdanne oxygen-rige molekyler udledt fra biomasse, til mere værdifulde kemikalier. De indledende eksperimenter fandt frem til at reaktionen kan udføres i en autoklav ved 230 °C, når 1,2-decanediol får lov til at reagere med 5 mol% ammonium metavanadat (NH_4VO_3) i isopropanol. Efter 17 timer kunne et udbytte af 1-decen, svarende til 50 mol% af den oprindelige mængde substrat, blive påvist med gaskromatografi.

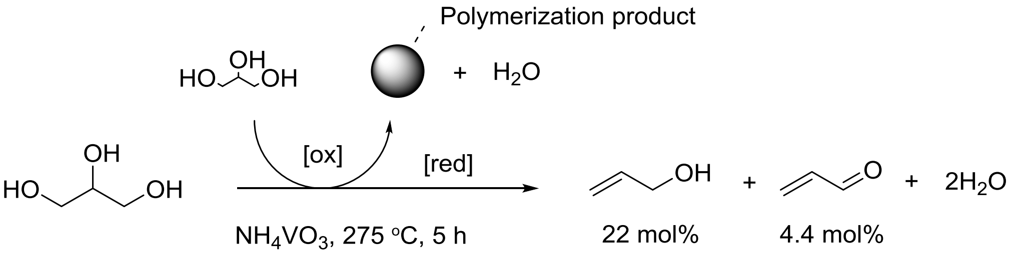
Forskellige alkoholer er blevet brugt som opløsningsmiddel, og deres evne til at reducere vanadium tilbage til det reaktive oxidationstrin testet. De sekundære alkoholer gav generelt langt bedre udbytte end de tilsvarende primære alkoholer, og isopropanol blev derfor brugt i den videre forskning. Katalysatoren blev undersøgt nærmere ved at sammenligne produktudbytterne fra reaktioner katalyseret af en række forskellige vanadium forbindelser. De fleste af de undersøgte katalysatorer gav de samme resultater, og NH_4VO_3 blev derfor anset som et godt valg, på baggrund af dets tilgængelighed og lette håndtering. På trods af at lave turnover numre blev fundet i batch eksperimenterne, viste katalysatoren sig at være meget mere robust, når den genanvendes, inden den når at deaktivere.

Vanadium katalyseret DODH blev fundet til at udvise en helt unik selektivitet rettet mod substrater indeholdende præcis én primær og én sekundær hydroxyl gruppe. 3,4-Hexanediol gav således intet udbytte af alken og begge stereoisomere af 1,2-cyclohexandiol reagerede næsten ikke. Substrater stabiliseret af konjugation, såsom hydrobenzoin, viste sig dog at gennemgå spaltning ved oxidation, hvormed to aldehyder bliver dannet. Diolernes reaktivitet blev også fundet til at afhænge kraftigt af den interne orientering af hydroxylgrupperne. Et skarpt fald i produktudbytte kunne observeres da *cis*-1,2-cyclohexanediol blev tilsat reaktionen af 1,2-hexanediol, hvilket er i kontrast til tilsætning af *trans* stereoisomeren. En mulig årsag er at *trans* isomeren ikke kan koordinere til metallet med begge hydroxylgrupper samtidigt, og dermed blokere reaktionen. Glycerol viste sig heller ikke at reagere, hvorimod 1,2-propanediol og 3-isopropoxy-1,2-propanediol gennemgår DODH, til propen og 3-isopropoxy-1-propene.



Det blev påvist, at det vand der formes når reaktionen forløber, hæmmer deoxydehydreringen så tilstrækkeligt meget, at fjernelse af vandet kunne være en mulig vej til at opnå udbytter over 50 mol%. Molekylesier, 2,2-dimethoxypropan, triethyl orthoester og en række af andre metoder til at fjernelse af vand, blev afprøvet og analyseret.

Vanadium katalyseret reaktiv destillation af glycerol er også blevet udviklet. Reaktions opsætningen og betingelserne blev optimeret til at sikre en hurtig separation af produkterne fra resten af reaktionsblandingen. Kun 1 mol% NH_4VO_3 var nødvendig for at opnå total omdannelse af 23 g glycerol, med direkte opsamling af en blanding bestående af allyl alkohol, acrolein og vand. De bedste resultater blev opnået ved opvarmning til 275 °C, hvormed 22 mol% allyl alkohol og ca. 4 mol% acrolein, blev dannet i løbet af 5 timer. Et sort materiale var tilbage i reaktionsflasken efter endt reaktion, og dets sammensætning blev analyseret ved brug af element analyse. Materialet blev senere bestemt til nok at være en polymer, der hovedsageligt er opbygget af acrolein, samt allyl alkohol og glycerol monomerer. Den katalytiske reaktivitet af $MeReO_3$, $(NH_4)_6Mo_7O_{24}\cdot 4H_2O$ og NH_4VO_3 blev sammenlignet, og vanadium fundet til at give mere allyl alkohol end rhenium, hvilket var overraskende på grund af den højere DODH aktivitet for sidstnævnte.



Abbreviations

1°OH	Primary alcohol
2°OH	Secondary alcohol
3-HPA	3-Hydroxy-propanoic acid
5-HMF	5-Hydroxymethylfurfural
ABE	Acetone-butanol-ethanol process
acac	Acetyl acetonato
AHM	$(NH_4)_6Mo_7O_{24}$•$4H_2O$
APR	NH_4ReO_4
BHT	2,6-di-*tert*-butyl-4-methylphenol
bp.	Boiling point
Bu	Butyl group
Bu_4NOH	tetrabutylammonium hydroxide
$CDCl_3$	Deuterated chloroform
Cel	Cellulose
Cp^*	Pentamethylcyclopentadienyl
$Cp^{ttt}ReO_3$	1,2,4-Tri(tert-butyl)cyclopentadienyl trioxo- rhenium
D_2O	Deuterated water
DFT	Density functional theory
DHB	2,5-dihydroxybenzoic acid
$(DHQD)_2PHAL$	Hydroquinidine 1,4-phthalazinediyl diether
$(DHQ)_2PHAL$	Hydroquinine 1,4-phthalazinediyl diether
dipic	Dipicolinate
DMSO	Dimethyl sulfoxide
DMSO-d	Deuterated dimethyl sulfoxide
DODH	Deoxydehydration
E_a	Activation energy
ESI-MS	Electrospray Ionization Spectroscopy
GC	Gas chromatography
GCMS	Gas chromatography coupled mass spectrometry
GDP	Gross domestic product
HC	Hydrocarbon
HDO	Hydrodeoxygenation
Hem	Hemicellulose
HHV	Higher heating value
HPLC	High-pressure liquid chromatography
*i*PrOH	Isopropanol
IR	Infrared spectroscopy
KIE	Kinetic isotope effect
LCMS	Liquid chromatography coupled mass spectrometry
LHV	Lower heating value

Lig	Lignin
MALDI-HRMS	Matrix-assisted laser desorption/ionisation high resolution mass spectrometry
Me	Methyl group
MPV	Meerwein-Ponndorf-Verley reaction
MTO	Methyltrioxorhenium
NMR	Nuclear magnetic resonance spectroscopy
OPP	Oppenauer Oxidation
PAA	poly(acrylic acid)
PE	Polyethylene
PhCl	Chlorobenzene
PhH	Benzene
PP	Polypropylene
PPh_3	Triphenylphosphine
PPP	Purchasing power parity
PTFE	Polytetrafluoroethylene
PTT	poly(trimethylene terephthalate)
Py	Pyridine
RF	Response factor
salhyd	Salicylaldehyde hydrazide
TFA	Trifluoroacetic acid
THF	Tetrahydrofuran
TON	Turn-over number
Tp´	Hydridotris(3,5-dimethylpyrazolyl)borate)
tpp	5,10,15,20-Tetraphenyl-21H,23H-porphyrine

Contents

1 Introduction

1.1 The Terawatt Challenge

As the world population is estimated to grow by 21% between 2014-35 and people meanwhile gets the financial power to buy cars and other energy consuming equipment, the world wide consumption of energy raises to new challenging levels (Table 1). Richard Smalley, named it the "The Terawatt Challenge" and with good reason.[1] According to the BP 2016 Energy Outlook report, the global primary energy consumption was 17.4 TW in 2015 and estimated to increase to 23.0 TW by 2035.[2] Most of the energy is produced by burning fossil fuels; oil, coal, and natural gas which are all carbon based sources of energy that have accumulated in the crust of the earth for ages (Figure 1). Burning the fossil fuels for energy production causes increased global warming and public health issues.[3] Obtaining new renewable ways to produce energy and refinement of already known technologies is therefore of huge political interest and may very well be the biggest challenge, that science is expected to solve in the near future.

The most common alternative ways to produce energy, that does not rely on burning fossil fuels, still need refinement or suffer from insufficient supplies of natural resources. Hydropower is limited

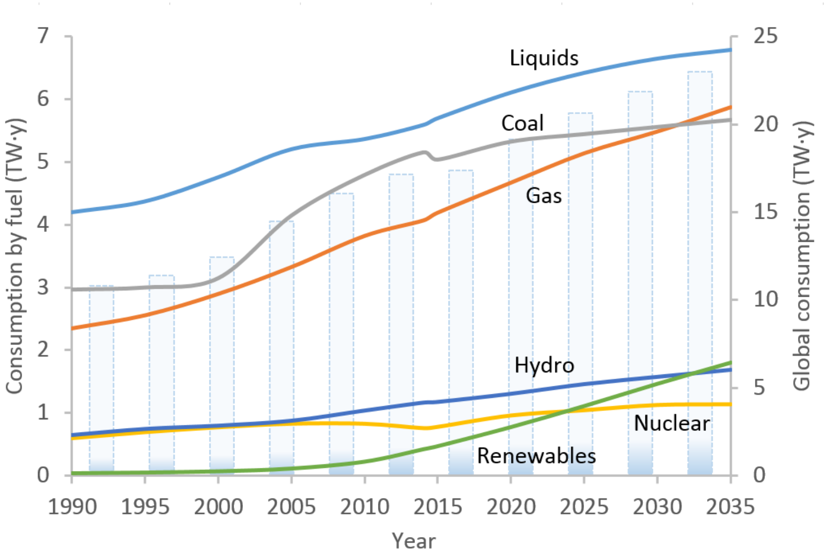


Figure 1. Global annual energy consumption divided into fuel type. *Liquids*: oil, biofuels, gas-to-liquids and coal-to-liquids. *Renewables*: wind power, solar electricity and other renewables. Data source: GP, *2016 Energy Outlook*.

Table 1. Growth and Share of the Total Primary Energy Consumption for Different Types of Fuel, at Present and in the Near Future.

	Growth 2014-35 (p.a.)	Growth 2014-35 (cumulative)	2014 (share)	2035 (share)
Primary Energy	1.4%	34%	100%	100%
Oil	0.9%	20%	32%	29%
Gas	1.8%	44%	24%	26%
Coal	0.5%	10%	30%	25%
Nuclear	1.9%	50%	4%	5%
Hydro	1.8%	45%	7%	7%
Renewables [a]	6.6%	285%	3%	9%
Population	0.9%	21%		
GDP ($2010 PPP)	3.5%	107%		
CO2 emissions	0.9%	20%		

Expected increase in population and CO_2 emissions. GDP, expressed as purchasing power parity (PPP), at 2010 prices. [a] Includes biofuels.

to specific geographical areas where it is suitable to build facilities able to harvest this sort of energy, and is thus expected to stay constant at a 7% share of the total primary energy usage until 2035 (Table 1). The share of nuclear power is only expected to increase by 1% as this source of energy suffers from radioactive waste and safety issues that has caused strong public opposition against the technology. Nuclear power could probably be expanded drastically if needed, but is not an obvious solution to the liquid fuel transport sector, as it requires an effective way to store the energy. The best solution to the terawatt challenge is for science to develop methods, that as directly as possible utilize the energy from the sun, to obtain high energy fuels that are based on renewable resources.

The most abundant and renewable carbon resource on earth is biomass, thus chances are, that fuels obtained from this source will play a major part in tomorrow's energy sector. It is also reflected in the GP Energy Outlook, in which renewables (biofuels) are estimated to grow by an impressive 285% until the year 2035 (Table 1). However, renewables are only estimated to constitute 9% of the total primary energy consumption at that point, which illustrates that more science and technology have to be invented. The next section will zoom in on the renewable biomass pool, and shortly introduce the different types of compounds that can be obtained and further processed into valuable chemicals.

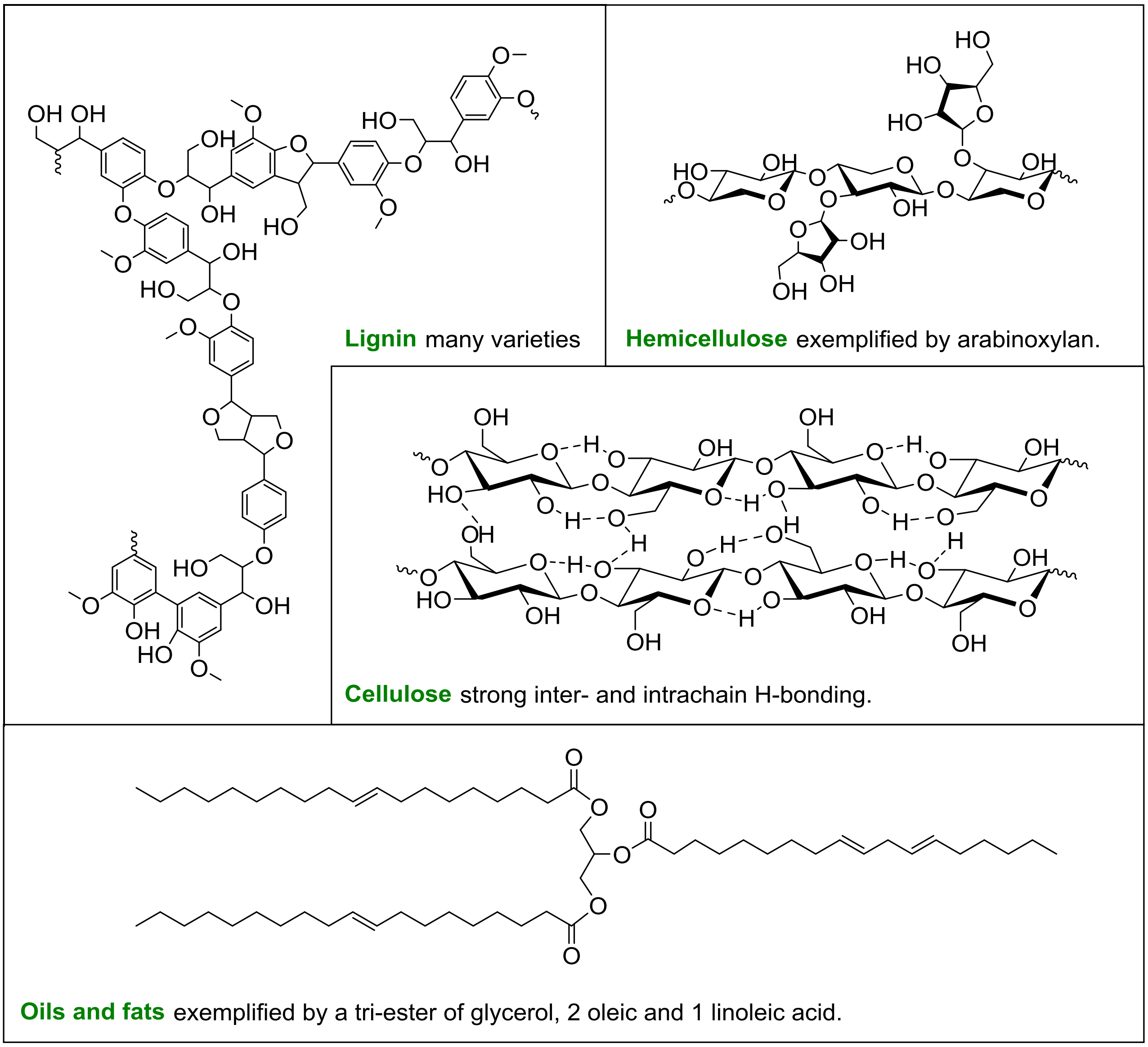


Figure 2. The four major components of biomass are cellulose, hemicellulose, lignin and oils/fats.[4]

1.1.1 The Renewable Biomass Resource

Biomass has been defined by the UK forestry commission to include any biological material derived from living or recently living organisms, thus chemicals of fossil origin are excluded.[5] Biomass that can easily be used for production of food, usually consist of starch and mono- and disaccharides containing fructose or sucrose units for example. The non-digestible biomass, that can be used to produce chemicals, may be divided into three main components; cellulose (Cel), hemicellulose (Hem) and lignin (Lig) (Figure 2). However, some plant seeds also contain oils which can be used for biodiesel production.[6] The amounts that can be extracted of the three components,

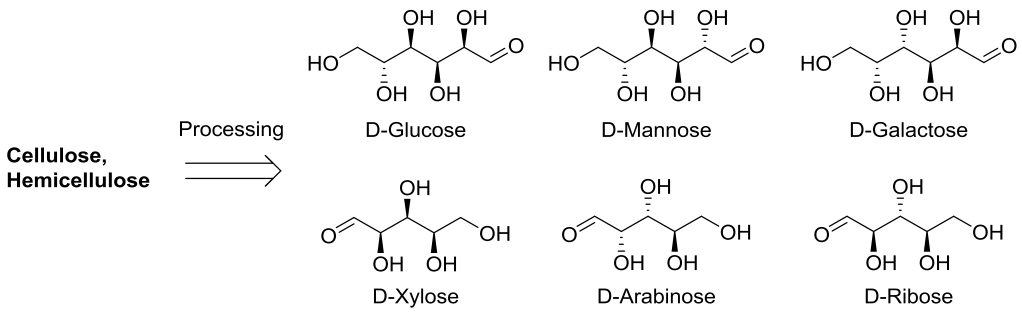


Figure 3. Representation of some carbohydrates that are obtained from cellulose and hemicellulose.

certainly depend on which resource is being implemented. On average, herbaceous and agricultural biomass generally contains more cellulose (Cel: 46.1, Hem: 30.2, Lig, 23.7 wt%) than wood and woody material does (Cel: 39.5, Hem: 34.5, Lig, 26 wt%), which make it a better source of this component.[7] Also, recycling of paper is a good way to obtain cellulose, as paper is produced from that component in the first place (Cel: 68.1, Hem: 17.1, Lig, 14.8 wt%).

In fact, cellulose is the most abundant organic compound on earth.[4] It consists of long chains of D-glucose units that can form inter- and intrachain hydrogen bonds, which cause cellulose to be a crystalline and hydrophobic material resistant towards hydrolysis. Hemicellulose however, is chemically more complex because it is constructed from both 5-carbon carbohydrates, such as xylose, arabinose and ribose, as well as 6-carbon compounds; glucose, mannose and galactose (Figure 3). The possible branching of the individual chains in hemicellulose prevents a structured organization of the chains and thereby the formation of a crystalline material. For this reason, it is easier to hydrolyze hemicellulose than cellulose into smaller polysaccharides.[4]

D-glycose is the 6-carbon sugar in which the stereocenters on carbons C2-C5 are set in a specific arrangement relative to each other, whereas L-glucose is the compound where all the stereocenters are reversed (Figure 4). Cellulose obtained from biomass consist solely of D-glucose monomers and

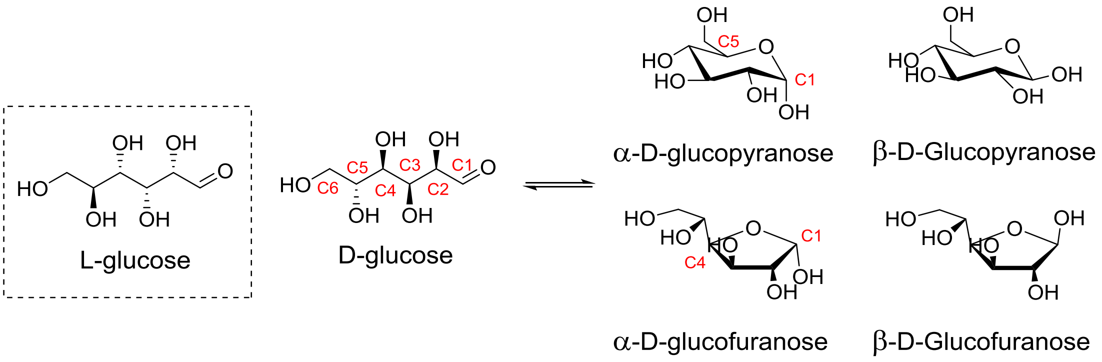


Figure 4. Open-chain L- and D-glucose and cyclic forms of D-glucose.

Table 2. The Equilibrium Composition of Isomers When Carbohydrates are Dissolved in Water at 31 °C.

Carbohydrate	α-pyranose (%)	β-pyranose (%)	α-furanose (%)	β-furanose (%)	Open-chain (%)
Glucose	38.0	62.0	0.5	0.5	0.002
Fructose	2.5	65.0	6.5	25.0	0.8
Xylose	36.5	63.0	0.3	0.3	0.002

L-glucose is therefore not interesting in a bioresource perspective.[8] The ring structures of D-glucose are formed when either the hydroxyl group on the C4, or the C5 carbon, undergo nucleophilic attack on the aldehyde. Depending on which one of the hydroxyl groups that react, either a 5-membered furanose or a 6-membered pyranose ring structure is formed. Also, because the nucleophilic attack may happen on either side of the carbonyl, two different stereoisomers of both the cyclic furanose and pyranose forms arise, which give a total of 4 different compounds (Figure 4). The two sets of stereoisomers are termed α or β depending on the relative orientation of the hydroxyl group at the anomeric carbon (C1) and the side-chain at carbon C4 or C5. The β-form is the one that has both groups on the same side of the plane going through the ring, whereas the α-form has the groups on opposite sides. When the carbohydrates are diluted in water, an equilibrium between their α- and β-forms are met. A percentage distribution of the isomers for glucose, fructose and xylose are given in Table 2.[9] The open-chain structures are generally very rare, yet they are often used in presentations as they make it easier to distinguish the different carbohydrates from one another. For glucose and xylose, the pyranose form is dominant in water at 31 °C, whereas fructose take form as both pyranose and furanose ring structures. Even though the distribution of isomers may be different in another solvent, these structural changes should be considered when planning to use the carbohydrates in chemical engineering.

The most difficult component to process in the biomass pool is lignin, which is a big complex structure with many aromatic segments (Figure 2). Lignin is thus a potential bioresource to aromatic compounds, though more research on extraction and workup has to be done before it can be fully utilized. The Norwegian biorefinery, Borregaard, is however already producing vanillin from lignin obtained from *Norwegian Spruce*, for use in a variety of different food applications.[10]

To further deliberate on biomass utilization it is useful to consider the effective H/C ratio, which for a compound only consisting of C, H, and O, is defined as in eq. 1. The ratio, provides an idea of the degree of oxygenation of a molecule and its energy density.[11]

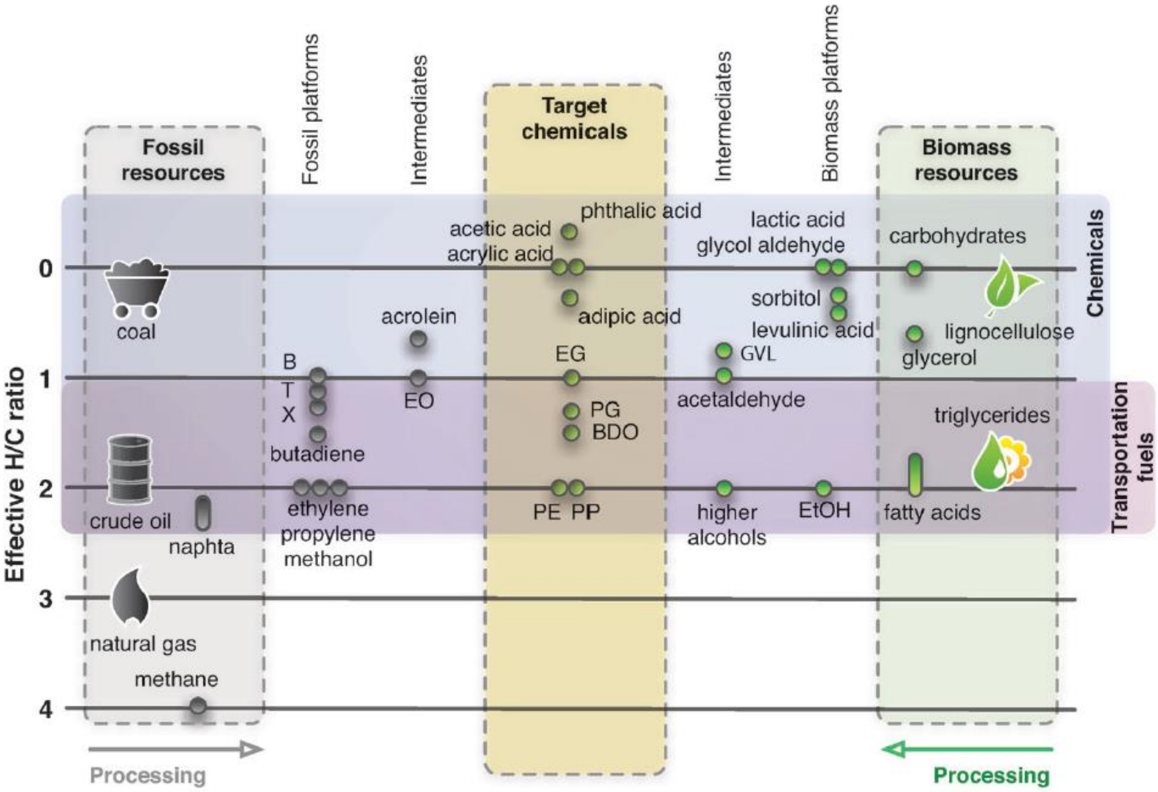


Figure 5. Road map for biomass and fossil fuel feedstocks, to be turned into transportation fuels or commodity chemicals. The map is spanned by the effective H/C ratio of the compounds, versus the amount of expected processing. Benzene (B), 1,4-butanediol (BDO), ethylene glycol (EG), ethylene oxide (EO), γ-valerolactone (GVL), polyethylene (PE), propylene glycol (PG), polypropylene (PP), toluene (T), xylenes (X).[11]

$$\text{Effective H/C ratio} = \frac{n(\mathrm{H}) - 2n(\mathrm{O})}{n(\mathrm{C})} \qquad \text{eq.1}$$

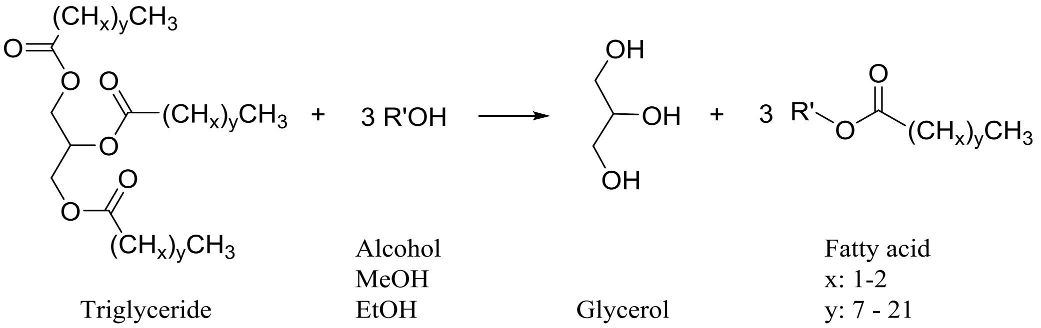
The carbohydrates depicted in Figure 3 have H/C ratios close to zero and are therefore located in the upper right corner of Figure 5. Processing them into transportation fuels or chemicals originally produced from fossil resources, requires methods to increase the H/C ratio, i.e. remove oxygen. Examples of high-value chemicals that may be obtained this way are ethylene and propylene, for production of polyethylene (PE) and polypropylene (PP), respectively.[12] Another possibility for valorization of biomass is to change the chemical functionality of the molecules without significantly lowering the amount of oxygen. This method has the advantage that it is possible to reach important compounds which are otherwise difficult to obtain from petrochemicals. They are typically located in the blue box named “chemicals” in Figure 5**,** and examples hereof are; levulinic acid, lactic acid, acrylic acid and glycol aldehyde.[4,11]

The fossil fuels that we currently depend on, are based on biomass that have resided underground at high pressures for so long, that it has been reduced to chemicals with almost no oxygen content i.e. H/C ratios between 2 and 4. When these compounds are burned and the carbon fully oxidized to CO_2, lots of thermal energy is released. On the other hand, most of the raw biomass material already contains a lot of oxygen thus, the energy generated when it is burned is insufficient for most applications. A common way to compare the fuel properties of different chemicals, is to look at the heating values and energy densities. The heating value of a chemical is the amount of heat released when it is burned to CO_2 and H_2O under ambient conditions (i.e. 25 °C, 1 atm.). In the case of higher heating values (HHV), the energy in the formed water vapor is included, whereas the lower heating value (LHV) excludes it. The higher heating value of a chemical may be estimated from the elemental composition, as shown in eq. 2.

$$\mathrm{HHV(MJ/kg)} = 0.3137 \cdot n(\mathrm{C}) + 0.7009 \cdot n(\mathrm{H}) + 0.0318 \cdot n(\mathrm{O}) - 1.3675 \qquad \text{eq.2}$$

The equation illustrates that oxygen atoms do not contribute nearly as much as carbon and hydrogen does to the estimated higher heating value of the chemical. The calculated HHV of glucose and hexane is thus 17.6 and 36.3 MJ/kg, respectively, and the oxygen free C_6 molecule is therefore a better fuel in this perspective. Experimentally obtained HHVs of interest are; hexane: 48.3, ethanol: 29.7, gasoline: 47.3 and hydrogen (l): 141.8. MJ/kg.[13] Even though H_2 has an impressive heating value, the energy density is pretty low. For liquid hydrogen, it is only 10.1 MJ/L, whereas ethanol and conventional gasoline have energy densities of 24.0 and 34.8 MJ/L, respectively.[13]

Fuels that are based on gases are generally troublesome in applications that use a lot of energy and have a limited amount of space (e.g. cars and trucks). The compression of the gas also requires energy, and if that energy is not used when the gas is released, it is wasted. The compressed gases, also have to be stored and transported in containers that are specifically suited for the purpose. It is therefore convenient to develop liquid biofuels because they may be implemented directly into the established fossil fuel infrastructure and thus, lower the expenses associated with a transformation from a fossil fuel governed society, into a society depending on renewables. Yet, biofuels as a standalone solution to the terawatt challenge is thought to be impossible, because the photosynthesis is too inefficient to produce enough biomass on the available land space, for both energy and food production.[14,15]



Scheme 1**.** Transesterification of triglycerides to fatty acids (biodiesel).

Two major types of biofuels are currently in use, that is; bioethanol which is produced by fermentation of sugars or starches,[16] and biodiesel which is produced by alkali-catalyzed transesterification of triglycerides obtained from soybean-, rapeseed- or palm oil (Scheme 1).[14,17] Whether the diesel is produced from biomass or fossil resources, has a large impact on the overall CO_2 emissions when both production and later burning of the fuels is considered. In this way, an estimated 78% less CO_2 is emitted when biodiesel is implemented rather than normal diesel.[18] The transesterification of triglycerides not only yields three equivalent of fatty acid esters (biodiesel), but also 1 equivalent of glycerol.[19] With an expected increase in the world production of biodiesel from 11.1 Mt in 2014 to 41.4 Mt by 2025, huge amounts of glycerol can be expected to be produced as well.[20] The current market for glycerol is too small to take up these tremendous amounts thus, new uses have to be discovered and developed to make the overall production of biodiesel more attractive. The economic aspects in biorefineries are very important if the European political goal of reducing greenhouse gas emissions by 80% between 1990 and 2050 is to be met.[21]

1.1.2 Valorization of Glycerol.

Glycerol is one of the most interesting biomass derived compounds, because of the mismatch in the amounts produced compared with the limited applications. Much research has been done in an attempt to find processes that can turn glycerol into valuable chemicals. In order to do this, the oxygen content usually has to be lowered in a selective way that preserves some of the functionality. In this context, reduced compounds such as 1,2-propanediol, 1,3-propanediol, allyl alcohol, acrolein, acrylic acid, propylene and glycidol are interesting target chemicals, because they are either directly or indirectly used as monomers for polymerization into various types of plastics (Figure 6).[22,23]

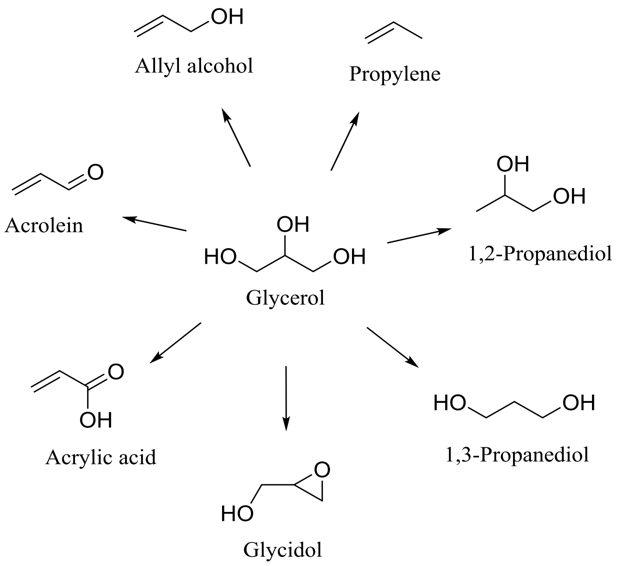


Figure 6. Valuable platform chemicals for production of polymers, that may be obtained from waste glycerol.

- **Propylene**, is used to make polypropylene (PP) which is the most common polymer worldwide, next to polyethylene (PE). Right now, propylene is produced from petrochemicals and the production in 2011 was estimated to be 47 million ton/y.[12]
- **Acrylic acid**, can polymerize to poly(acrylic acid) (PAA), which is another high-value commodity chemical. PAA is used in adhesives and coatings, such as latex and acrylic paint. It is mainly produced by oxidation of propylene.[12] Since 2008, the companies Cargill and Novozymes have been working on a process to ferment sugars into 3-hydroxy-propanoic acid (3-HPA), which can be dehydrated to acrylic acid in a subsequent step.[24]
- **Allyl alcohol**, is difficult to polymerize as a clean, high weight polymer due to possible abstraction of one of the allylic H-atoms to form a radical that is in resonance with an enol form, and stabilized by tautomerization (Figure 7).[25] The stabilized radicals are much less reactive than those formed through addition to the double bond. They are therefore more likely to react with other radicals, thus terminating the reaction and leading to unwanted chain structures. Instead, allyl alcohol may be used as a co-polymer in the synthesis of polyesters. Also, production of glycidol is done by epoxidation of allyl alcohol.[22]
- **Acrolein**, is mostly used in the synthesis of methionine.[26] Polymerization of acrolein leads to low weight oligomers with mixtures of aldehyde, ether and vinyl functional groups. Research is still done in this field as the aldehyde groups holds interesting properties in protein modification and enzyme immobilization.[27]

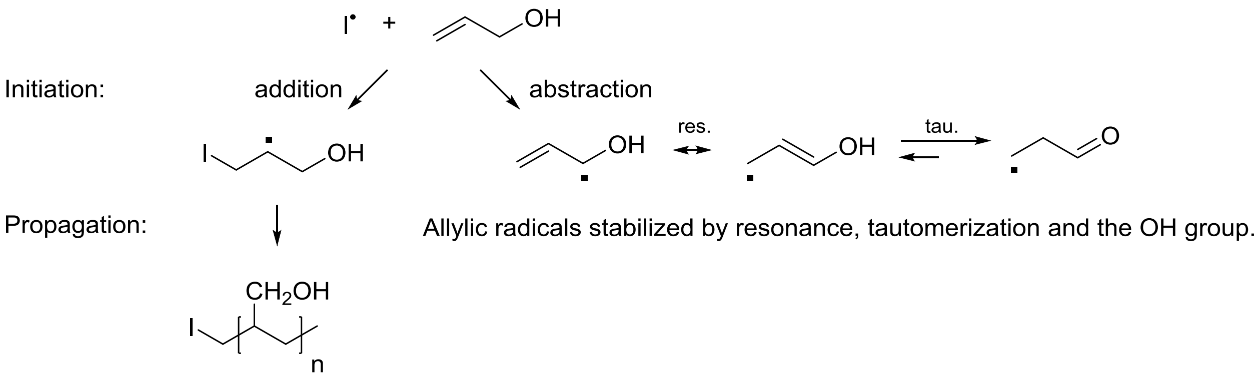


Figure 7. Polymerization of allyl alcohol through addition of an initiator (I) to the double bond.

- **Glycidol**, is used in the preparation of polyglycerol esters, and as a stabilizer for natural oils and vinyl polymers.[22]
- **1,3-propanediol**, is used to make poly(trimethylene terephthalate) (PTT).[12]
- **1,2-propanediol**, is a chemical used in pharmaceuticals, plastics, cosmetics and food.[23]

1.2 How to Remove Oxygen From Biomass

So far, many good reasons have been described as to why the oxygen content of biomass, and molecules derived from it, should be lowered. This section will begin with the non-catalytic pyrolysis reaction followed by an introduction to catalysis. The last part of the section will introduce some common catalytic methods that may be used to remove oxygen from chemicals.

1.2.1 Pyrolysis Reactions

The oldest known process, in which biomass is degraded at several hundred degrees Celsius, is called pyrolysis. Unlike gasification of biomass into syngas (CO, CO_2, H_2, CH_4)[28], pyrolysis products are obtained when the thermal decomposition is performed at oxygen concentrations that are far from enough to give full combustion of the biomass material (Scheme 2).[29] The products of pyrolysis is a complex mixture of different hydrocarbons (HCs), water and solid char. The HCs may be regarded as deoxygenated biomass, but the separation of the different hydrocarbons are complex and the method is therefore not suitable for production of specific chemicals. Pyrolysis is not a catalytic process and uses a lot of energy.

$$\text{Pyrolysis:} \qquad C_xH_yO_z \xrightarrow{\Delta} H_2O + HCs + char$$

$$\text{Gasification:} \qquad C_xH_yO_z + O_2 + H_2O \xrightarrow{\Delta} H_2 + CO_x + CH_4 + HCs + char$$

Scheme 2. Pyrolysis; Thermal decomposition of biomass with almost no oxygen present, to give water, hydrocarbons and char. Gasification; when controlled amounts of oxygen are applied, the major products are H_2, CO, CO_2 and CH_4.

1.2.2 Introduction to Catalysis

The main purpose of a catalyst is to lower the highest energy threshold in a reaction, thus speeding up the process and saving energy in the production. Figure 8 illustrates a theoretical energy profile for a reaction that is either non-catalytic or catalyzed. The catalyzed reaction may pass through more transition states to get to the final product Z, but the highest energy barrier (E_a) for doing so, must be lower in energy than in the uncatalyzed reaction. A catalyst could be anything (gas, liquid, or solid) as long as it is regenerated whenever product Z is formed (Figure 8).[30] They can be either homogeneous, heterogeneous, clusters of metals or biocatalysts (enzymes). The catalytic cycle often involves a change in the oxidation state of the metal (the catalyst) and a compound is therefore needed to either oxidize or reduce the metal back to the initial state. An

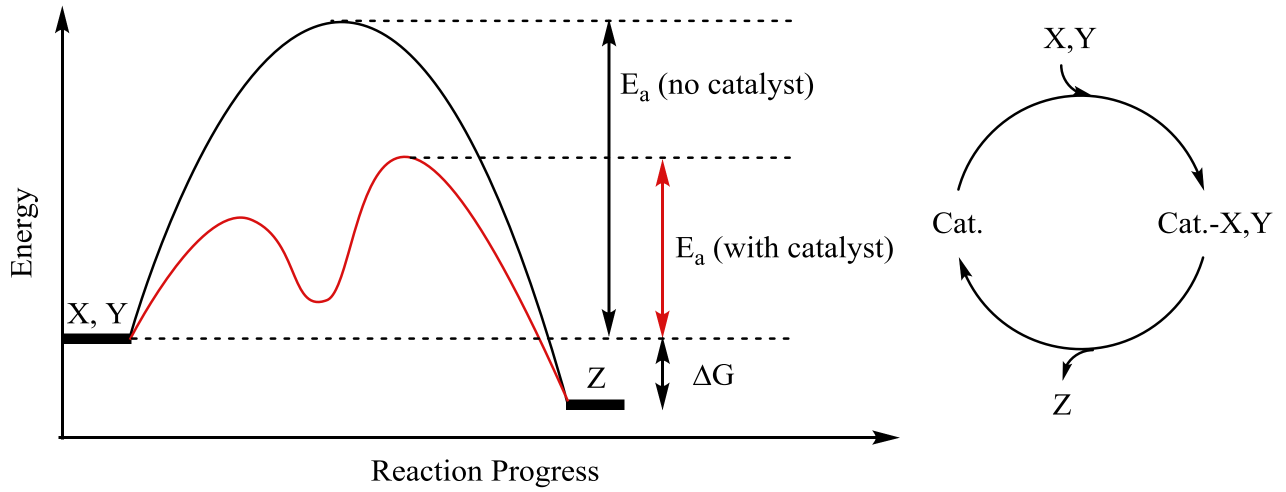
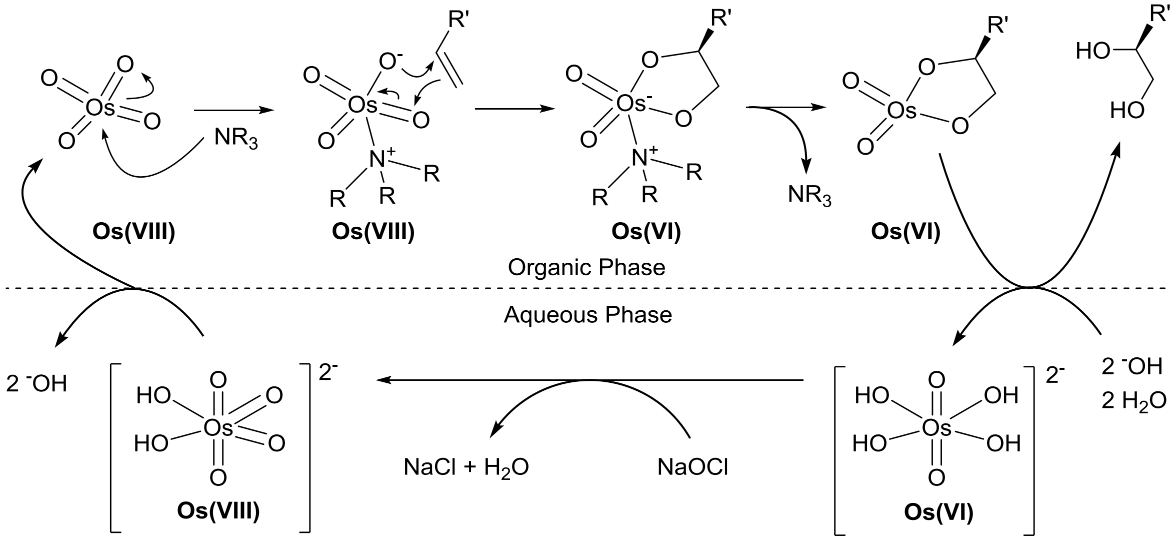


Figure 8. Energy diagram of a non-catalytic reaction that converts reactants X and Y into product Z. The red line shows the energy profile for the same reaction, when it is catalyzed.



Scheme 3. Osmium-catalyzed dihydroxylation of an alkene.

example is the osmium-catalyzed dihydroxylation of an alkene in which OsO_4 (VIII), in the presence of a tertiary amine, react with the alkene to form an Os(VI)-diolate (Scheme 3).[31] After release of the hydroxylated product, $K_2OsO_2(OH)_4$ (VI) is oxidized back to OsO_4 (VIII) by NaOCl or $K_3[Fe(CN)_6]$. The compound sacrificed for oxidation should be as cheap as possible or at least easy to regenerate.

The term homogeneous refers to catalysts that are dispersed in the same phase as the reactants and products. The high degree of dispersion increases the chance that the catalyst and the reactant will collide in the reaction mixture. This leads to a high activity of the individual metal centers and for this reason homogeneous catalytic systems usually perform well at very low catalyst concentrations and mild reaction conditions. The drawback of the homogeneous catalyst is, that it may be difficult to separate it from the resulting reaction mixture and that is often the problem that prevent it from being used on an industrial scale. However, solubility, reactivity and selectivity of the metal centers may be altered by organic ligands. Enantioselectivity may for example be controlled in the osmium-catalyzed dihydroxylation of olefins (Scheme 3) by using a chiral tertiary amine as ligand, such as $(DHQD)_2PHAL$ or $(DHQ)_2PHAL$ (Figure 9).[31] The selectivity can be predicted if the olefin is placed in a plane, so that the largest substituent on the double bond is in the bottom left corner of the plane in Figure 9, and the second largest substituent, in the top right. The steric effects of the chiral ligand, will direct the osmium center onto the top- or bottom face of the plane, when the $(DHQ)_2PHAL$ or $(DHQD)_2PHAL$ ligand is used, respectively.[32]

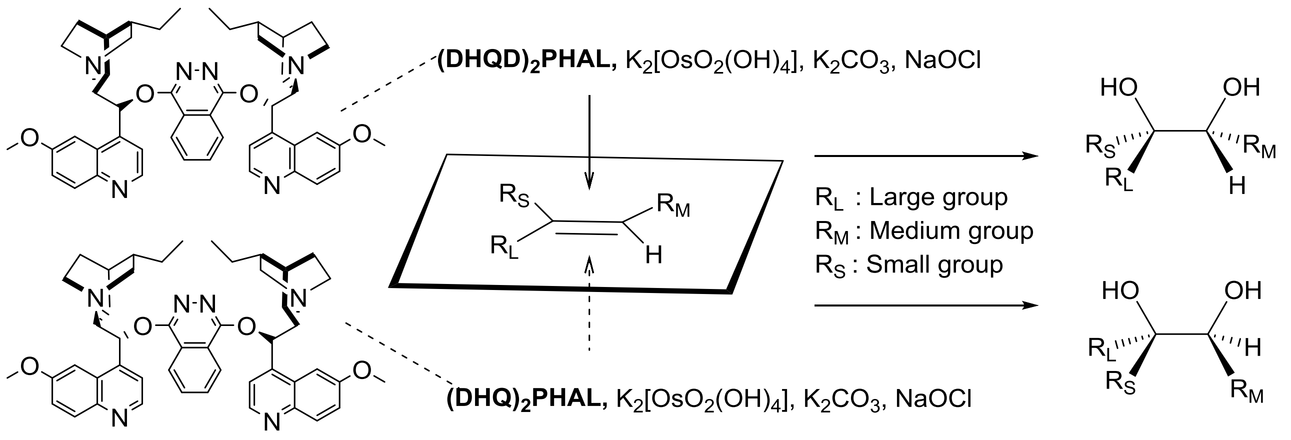
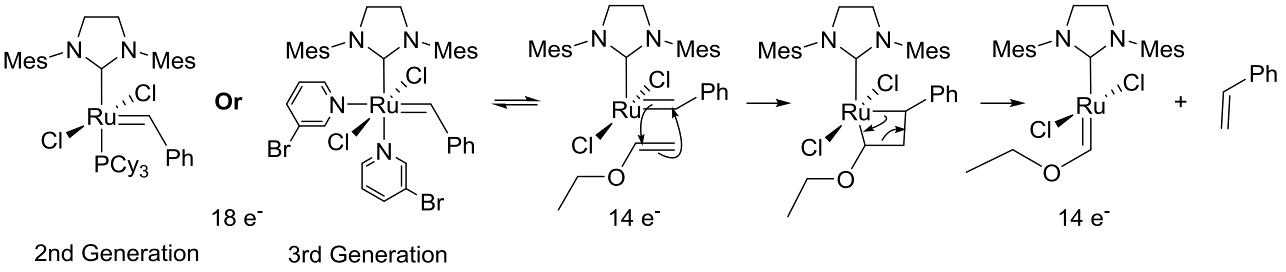


Figure 9. Enantioselectivity can be achieved in the osmium-catalyzed dihydroxylation of alkenes, by addition of one of the chiral ligands $(DHQD)_2PHAL$ or $(DHQ)_2PHAL$.

Changing one or more of the ligands on a catalyst, may also severely alter its reactivity. Metathesis reactions using Grubbs ruthenium complexes have been investigated thoroughly and progress has been obtained especially in regard to initiation rates. The 3rd generation Grubbs catalyst in Scheme 4, has been found to form the active 14 e^- Ru-complex six orders of magnitude faster than that of the 2nd generation. The initiation rates were investigated by reacting the complexes with ethyl vinyl ether, which react rapidly and irreversibly.[33,34]

The heterogeneous catalyst is usually a solid material while the reactants are liquids or gasses. The reactivity is often lower than with homogeneous catalysts as reaction may only take place at the surface of the solid. It is therefore desirable to create catalysts with big surface areas and many reactive sites. Because the heterogeneous catalytic systems occur between different phases, fast mass transfer of the reactants in the medium is also crucial. For this reason, the most common application is between a solid catalyst and a stream of gas containing the reactants. The most prominent advantage of the heterogeneous catalysts is that they are much easier to separate from the



Scheme 4. Initiation rates (for metathesis reactions) with the 2nd and 3rd generation Grubbs catalysts, investigated by the irreversible cycloaddition of ethyl vinyl ether.

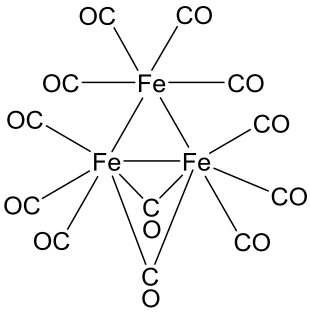


Figure 10. The metal carbonyl cluster, $Fe_3(CO)_{12}$.

rest of the reaction mixture, simply by filtration or centrifugation.[30]

Inorganic chemists define clusters as being groups of metals, at least three, that are either bonded or otherwise interacting directly with one another.[35] An example is the metal carbonyl cluster, $Fe_3(CO)_{12}$, depicted in Figure 10. It has three adjoining iron centers arranged in a triangle and the CO ligands are positioned in such a way that the hole cluster adopt a C_{2V} symmetry.[36] Atoms bonded in triangles are seldom in organic chemistry, but the high valence of the transition metals makes such connections more likely and elucidation of the structures and how they react more complex. Even though the catalytic properties of metal clusters have been investigated closely, they have not yet found application in industrial processes.

Enzymes are highly effective and selective catalysts that have been obtained or copied from living organisms. This means that they are built to function under mild reaction conditions and low concentrations of substrate. Most enzymes are usually only catalytically active at temperatures up to 20 °C above the temperature at which the living organism is growing.[37]

Whatever type of catalyst that is used, it is always important that it has a high selectivity for the products. Other compounds may be formed in sequential reactions, or in parallel, to the formation

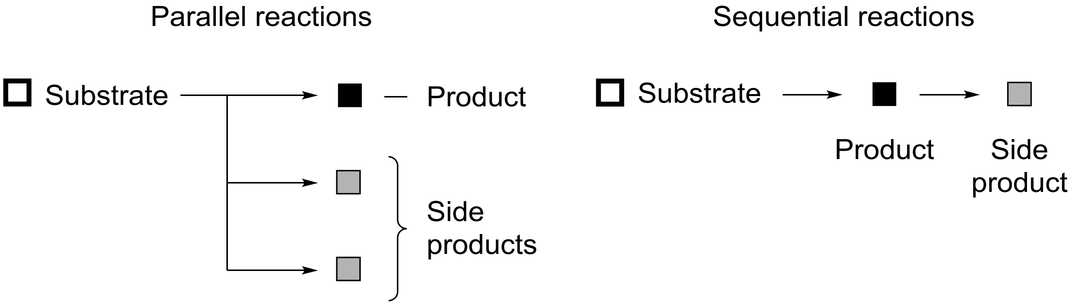
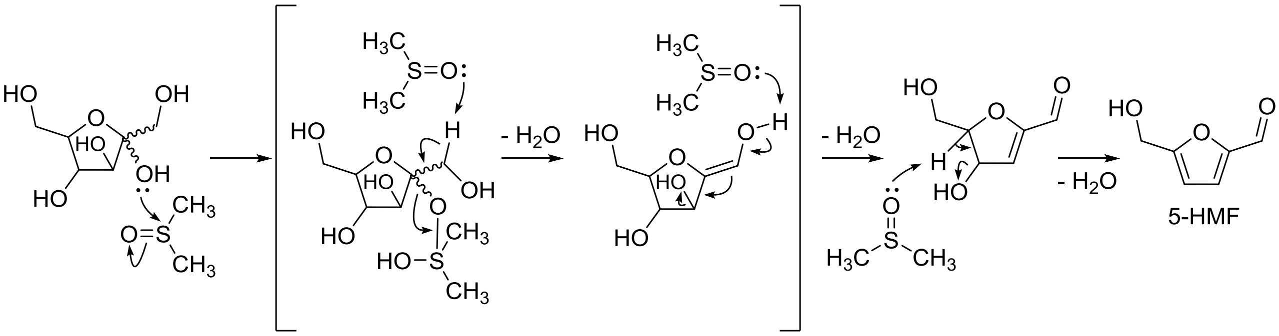


Figure 11. The creation of side products may be caused by either parallel or sequential reactions.

of product (Figure 11). A high selectivity will lower the cost of substrate and make separation of the desired chemical much easier. Catalyst selectivity can also refer to the ability of the catalyst to react with certain chemical groups within the substrate. This is called chemoselectivity, and may be a great feature if the starting material contains a lot of functional groups, of which only a few is supposed to react.

1.2.3 Dehydration Reactions

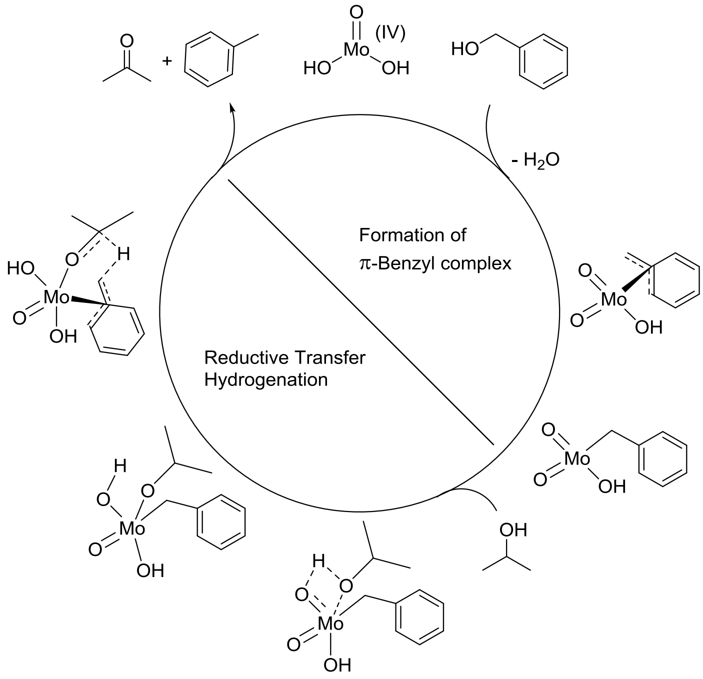
Dehydrations are reactions in which one or several molecules of water are removed from the substrate. A good example of a dehydration reaction that has been scrutinized for a long time, is the conversion of biomass derived hexoses into valuable 5-hydroxymethylfurfural (5-HMF). The compound can be produced from fructose, glucose, sucrose, and inulin in reactions that involve an acid catalyst, usually H_2SO_4.[4,38] When the dehydration is performed in water with a mineral acid, 5-HMF may be further hydrolyzed to levulinic acid and formic acid, which make the mechanism more difficult to investigate. The dehydration may however also be performed with dimethyl sulfoxide (DMSO) as the solvent and without an acid catalyst. In that case, DMSO is acting as the catalyst as well and the dry environment leads to a cleaner reaction that has been investigated with NMR. The mechanism is likely to be similar to the one with mineral acids and starts by a molecule of DMSO that interact with the OH group at the anomeric carbon. Then, two subsequent steps eliminates a pair of water molecules to form an intermediate structure that is further dehydrated to 5-HMF (Scheme 5).[39]



Scheme 5. Dehydration of D-fructose furanose to 5-HMF in DMSO at 150 °C.

1.2.4 Reduction Reactions that use Hydrogen

Hydrogen can be made to add across specific bonds within a molecule, if the right catalyst is used. Different classifications of these types of reduction reactions, depend on the nature of the bond that is broken and the products formed. If hydrogen adds across a double- or triple bond then it is called a hydrogenation reaction, but if it adds to a sigma-bond to break the molecule into two pieces, then it is termed a hydrogenolysis reaction. However, if water is one of the products, then it may be called a hydrodeoxygenation (HDO) reaction instead. The hydrogen does not have to be applied as a gas, but may for example be obtained by oxidation of an alcohol. An example of such a HDO reaction is depicted in Scheme 6, in which benzyl alcohol is reduced to toluene by a molybdenum (IV) catalyst, that meanwhile oxidizes *i*PrOH to acetone.[40] The reaction is expected to start by isopropanol reducing a molybdenum compound, such as $(NH_4)_6Mo_7O_{24}•4H_2O$ (AHM), into a catalytically active Mo(IV) species. DFT calculations show that subsequent reaction with benzyl alcohol may extrude a molecule of water and form a π-benzyl complex, that quickly rearranges into a σ-benzyl complex. Then another isopropanol molecule undergo reductive transfer hydrogenation with the phenyl ligand, through a series of intermediate steps, that in the end releases acetone and toluene and reforms the active Mo(IV) compound.

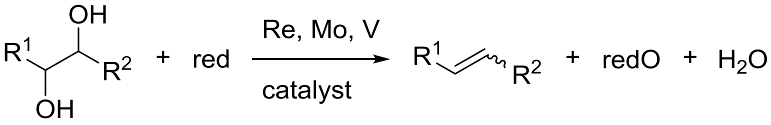


Scheme 6. Mo-catalyzed HDO of benzyl alcohol, using hydrogen obtained from oxidation of isopropanol to acetone.

1.2.5 Deoxydehydration Reactions

Deoxydehydration (DODH) is a process in which two vicinal hydroxyl groups are removed to form a product containing a double bond. This is a very good trade-off, because the formed double bond gives additional value to the product, as it may be used for subsequent synthesis of other chemicals or for polymerization reactions. Reaction Scheme 7, shows a generalized version of a deoxydehydration reaction where a molecule with a diol structure is converted into the corresponding alkene. Rhenium is the most investigated metal and typically gives high yields of alkene, but is also a very expensive precious metal. Less costly alternatives are Mo and V catalyzed DODH, but these metals have not been studied to the same extent. The process needs a cheap or recyclable reductant to reduce the metal back to the oxidation state in which it is catalytically active. Some of the cheaper reductants that have been implemented are; secondary alcohols, Na_2SO_3 and CO.

The drawback of DODH is that it probably won't work well on raw biomass, as the method requires a homogeneous reaction mixture to allow the catalyst to react with the target substrate. The method is therefore most suitable for valorization of oxygen rich molecules downstream from the biomass pool.[41,42]

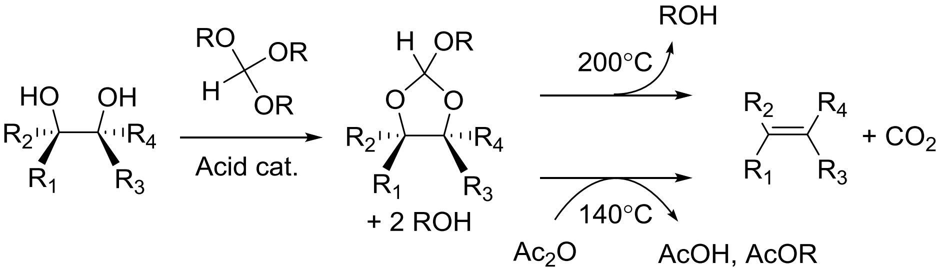


Scheme 7. Generalized Re-, Mo-, or V-catalyzed DODH of a vicinal diol into an alkene driven by the oxidation of a sacrificial reductant (red).

2 Vanadium Catalyzed Deoxydehydration with an Alcohol as Solvent and Reductant

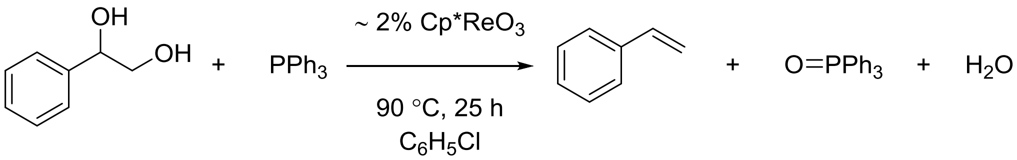
2.1 Introduction to DODH

The first non-catalytic DODH reaction was reported in 1963 by Corey and Winter[43]. This reaction involved two steps; one in which a cyclic thionocarbonate is formed by reaction of a vicinal diol with thiocarbonyldiimidazole, followed by reduction of the carbonate with $(MeO)_3P$ to release the alkene and CO_2. High yields of alkene were obtained and at relatively low temperatures (112 °C). One year later, in 1964, Crank and Eastwood[44] reported the two step non-catalytic deoxydehydration in which a substrate with the diol moiety reacts in an acid catalyzed condensation with triethyl orthoformate to form a dioxolane (Scheme 8).



Scheme 8. Two step DODH with an orthoformate.

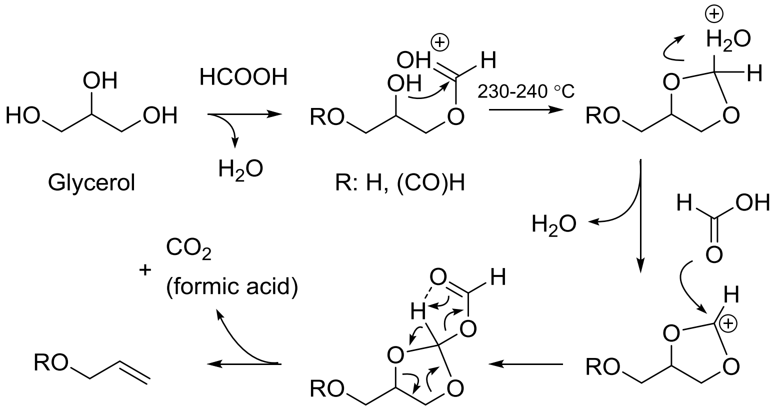
The following pyrolysis step, conducted between 180-200 °C, resulted in the desired alkene and the release of CO_2. Though it was proven in 1986 that addition of acetic anhydride lowers the reaction temperature to 140 °C, this reaction still suffers from the use of stoichiometric amounts of orthoformate, that ends up as carbon dioxide.[45] Years later, in 1996, the first catalytic DODH reaction was reported by Cook and Andrews.[46] They showed that 1-phenyl-1,2-ethanediol is converted to styrene in quantitative yields when exposed to ~2% Cp^*ReO_3 in chlorobenzene at 90 °C and with PPh_3 as the reductant (Scheme 9).



Scheme 9. The rhenium mediated DODH of 1-phenyl-1,2-ethanediol developed Cook and Andrews.

Even though these early findings were interesting, further research on DODH was not seen until 2009. At this point Arceo *et al.*[47] had investigated the non-catalytic reaction between formic acid and various polyols. This formic acid mediated DODH was found to convert 1,2-octanediol into 1-octene in 91% yield, and glycerol to allyl alcohol in 80% yield. A mechanism was suggested in which formic acid reacts with one of the primary alcohol groups to form a carbocation intermediate, that is attacked by another acid molecule to release the alkene and CO_2 (Scheme 10).

Especially the possible valorization of glycerol must have been interesting reading for people associated with the growing biodiesel economy. Figure 12, depicts the number of publications about DODH of vicinal diols and catalysis of glycerol, together with the world production of biodiesel between 1963 and 2016.



Scheme 10. Mechanism for the conversion of glycerol into allyl alcohol by formic acid.

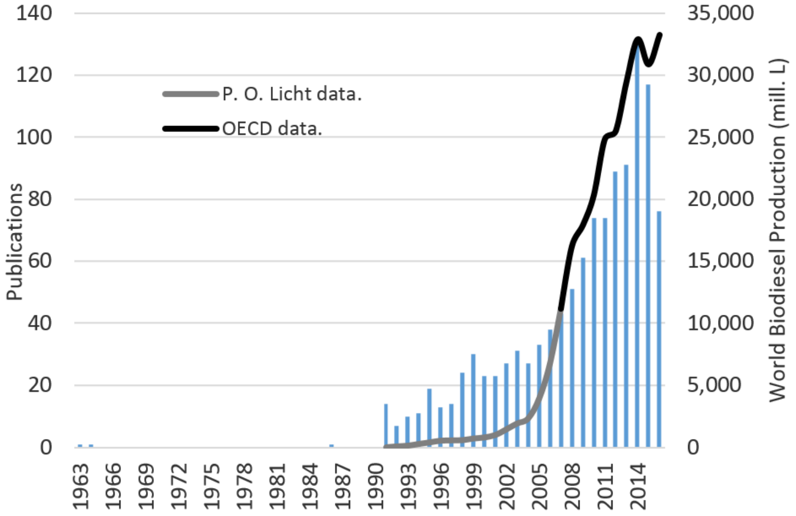


Figure 12. Bar plot: Publications about deoxydehydration and catalysis of glycerol; Source: Web of Science. Line plot: World production of biodiesel from 1991-2015 (2016 value is a prognosis). sources: P. O. Licht, *World Ethanol and Biofuels Report*;[48] OECD, *Agricultural Outlook 2016*.[49]

Since the first DODH reaction was developed, the goal has changed from a small scale synthesis point of view, into a matter of converting large amounts of biomass derived compounds for industrial production of chemicals. To ensure an economically viable and environmentally friendly process, a catalytic process must be developed. Of course research groups got inspired by the Re mediated DODH reported in 1996. Most of the literature is therefore based on Re and various different reaction conditions have been tested (Table 3). The catalyst is usually methyltrioxorhenium (CH_3ReO_3, MTO), but many other Re species have also been found to catalyze the reaction. Focus has mainly been directed onto homogeneous catalysts. Yet, Re situated on carbon has been investigated and found to deoxydehydrate 1,2-tetradecanediol into 1-tetradecene in 36% yield (Table 3, entry 11).

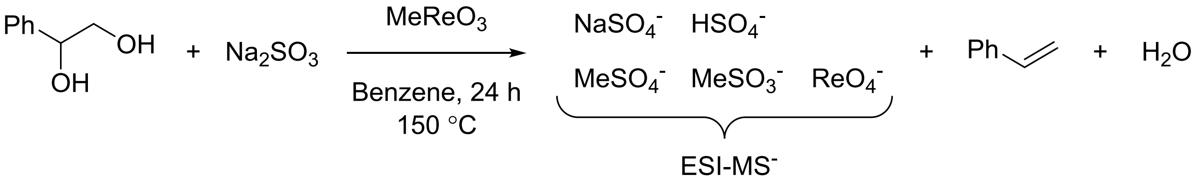
Most used solvents are benzene (PhH), chlorobenzene (PhCl) or tetrahydrofuran (THF), but may also be alcohols that meanwhile function as the sacrificial reductant. The reducing agent has often been triphenylphosphine (PPh_3) which is a strong, but very expensive reductant, that is not suitable for large scale usage. Applying H_2 to the DODH reaction has only resulted in low to medium yields of alkene for a long time, although very recent results on heterogeneous ReO_x-Au/CeO_2 have changed the scenario (Table 3, entry 16). Nicholas and others, have investigated a range of

Table 3. Historical Outline of the Scientific Developments of Early non-Catalytic and Re-catalyzed DODH of Vicinal Diols.

	Year	Catalyst	Red.	Solv.	Substrate	°C	C=C Yield
1[43]	1963	Non-catalytic	$(MeO)_3P$	2 step reaction	*meso*-Hydrobenzoin	112	92%
2[44]	1964	Non-catalytic	$CH(OMe)_3$	2 step reaction	Glycerol	220	90%
3[45]	1986	Non-catalytic	$CH(OMe)_3$	2 step reaction	1,2-Octanediol	140	95%
4[46]	1996	Cp^*ReO_3	PPh_3	Chlorobenzene	1-Phenyl-1,2-ethanediol	90	~99%
5[47]	2009	Non-catalytic	HCOOH	2 step reaction	Glycerol	240	80%
6[50]	2009	CH_3ReO_3	H_2	THF	1,2-Hexanediol	150	18%
7[51]	2010	Bu_4NReO_4	Na_2SO_3	THF	1-Phenyl-1,2-ethanediol	150	15%
8[52]	2010	$Re_2(CO)_{10}$	2° alcohol	2° alcohol	1,2-Tetradecanediol	170	83%
9[53]	2011	Bu_4NReO_4	Na_2SO_3	PhH/15-crown-5	1,2-Tetradecanediol	150	89%
10[54]	2012	CH_3ReO_3	2° alcohol	2° alcohol	Glycerol	170	90%
11[55]	2013	ReO_x/C	H_2	Benzene	1,2-Tetradecanediol	175	36%
12[56]	2013	CH_3ReO_3	$PhCH_2OH$	$PhCH_2OH$	Glycerol	170	47%
13[57]	2013	$Cp^{ttt}ReO_3$	PPh_3	Chlorobenzene	1,2-Octanediol	135	94%
14[58]	2014	$[(Py_4)ReO_2]Cl$	Zn	Benzene	1,2-Octanediol	150	90%
15[59]	2015	CH_3ReO_3	Indoline	1°alcohol	Glycerol	150	80%
16[60]	2016	ReO_x-Au/CeO_2	H_2	1,4-Dioxane	Glycerol	140	91%

Cp*= pentamethylcyclopentadiene.

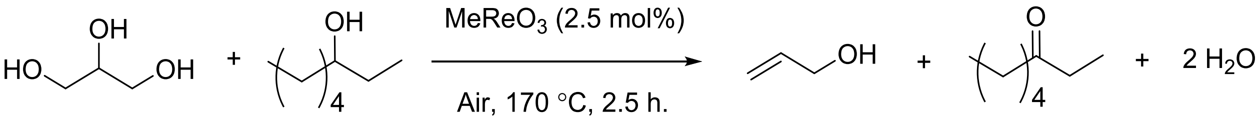
alternatives. One method that was reported, is the sulfite driven (SO_3^{2-}) DODH, in which Na_2SO_3 is oxidized to sulfate (SO_4^{2-}) as shown for 1-phenyl-1,2-ethanediol in Scheme 11. The resulting reaction mixture was investigated with negative ion ESI-MS analysis and the expected sulfate species detected. Yields up to 89% could be achieved for 1,2-tertradecanediol when performed with Bu_4NReO_4 in benzene, at 150 °C, for 110 hours, and with 15-crown-5 ether (Table 3, entry 9).[53]



Scheme 11. Sulfite driven DODH.

Nicholas and co-workers have also published results, in which benzyl alcohol is found to reduce Re in good yields, with benzene or toluene as the solvent.[56] Later in 2014, McClain and Nicholas[58] elucidated that elements like Zn, Fe, Mn, and even carbon, may be used in collaboration with ammonium perrhenate (NH_4ReO_4, APR), in benzene, to reduce 1,2-decanediol to 1-decene.

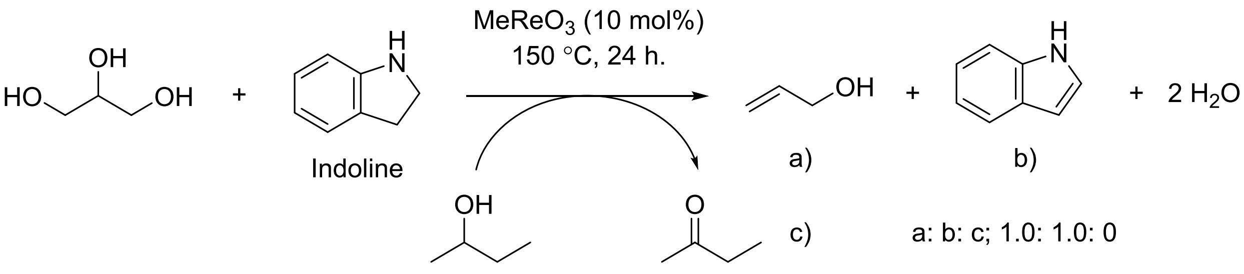
Systems that employ polar solvents, able to dissolve the oxygen rich feedstock, are more likely to become industrially feasible. Water would be a cheap and green solvent, but the lack of published results on the matter and the fact that water is released in the DODH reaction, is probably a sign that this solvent does not work very well. The next best solution is presumably to use an alcohol (Table 3, entry 8, 10). Apart from being a polar solvent, this procedure also opens up for the possibility to use the alcohol as the reductant. This has been found to work out very well with Re and a range of different substrates, which include sugars and sugar alcohols. Shiramizu and Toste,[54] showed that glycerol can be turned into allyl alcohol (90% yield) while using 3-octanol as the reductant (Scheme 12). The C_6 sugar; sorbitol, also reacted to give the corresponding triene in good yields (54%).



Scheme 12. Deoxydehydration of glycerol using 3-octanol as reductant.

Boucher-Jacobs and Nicholas[59] found that indoline may be used as the reducing agent in the Re-catalyzed DODH of a variety of different substrates using 1-butanol as the solvent (Table 3, entry

15). Also, competitive experiments between indoline and 2-butanol, revealed that indoline is a stronger reductant for MTO catalyzed DODH of glycerol (Scheme 13).



Scheme 13. Competitive experiment between indoline and 2-butanol as the reductant in the MTO catalyzed DODH of glycerol.

They concluded that in the case of rhenium, indoline has a higher H-transfer activity than 2-butanol and is thus a better reductant. Additionally, Shiramizu and Toste[54] concluded that secondary alcohols (2°OH) are better reducing agents than primary alcohols (1°OH) because the former generally gave better yields. For this reason it seems appropriate to put them up in the following order of increasing reduction ability; 1°OH < 2°OH < indoline. Indoline is commercially produced by hydrogenation of indole, and may therefore be regenerated if separated from the reaction

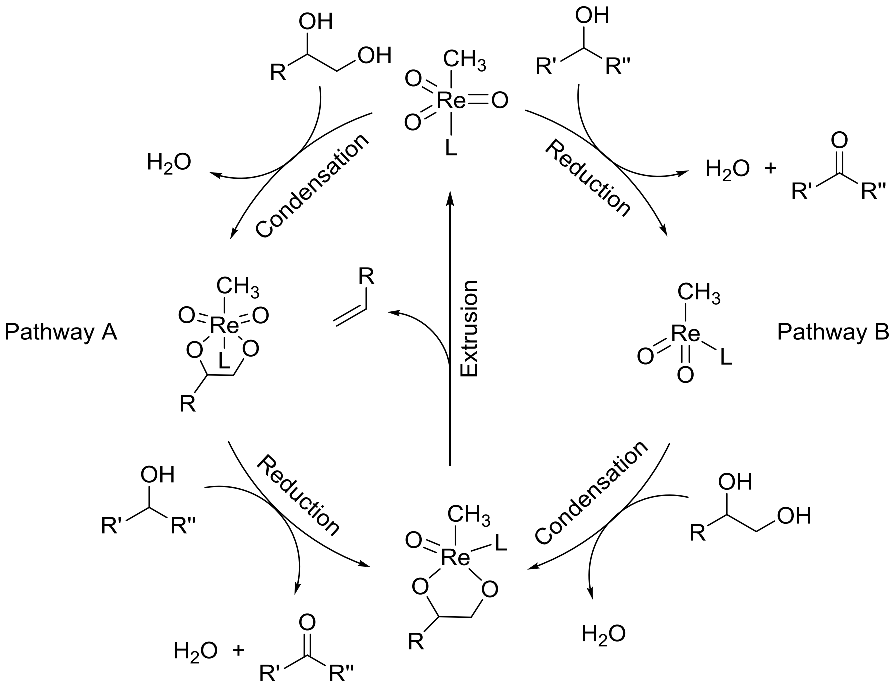
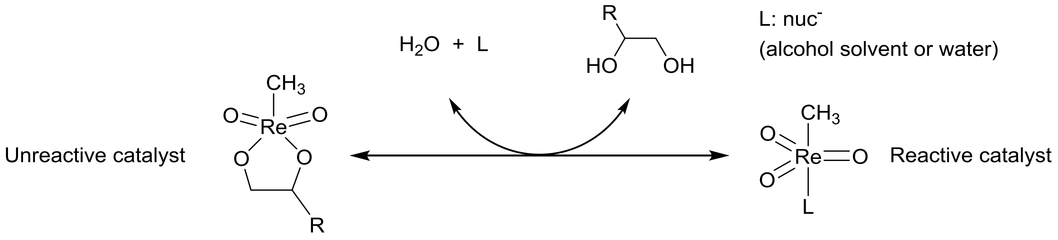


Figure 13. The two different pathways for the Re-catalyzed DODH of a vicinal diol, with a secondary alcohol as the reductant.

mixture.[61]

All the research on Re catalyzed DODH has resulted in a general agreement of a catalytic cycle that involves three steps; (A) condensation of a diol to the metal center, (B) reduction of the metal to the DODH active oxidation state, and (C) extrusion of the alkene (Figure 13). Rhenium is thus expected to change between oxidation states V and VII during the reaction. The two possible arrangements of the three steps have been referred to as pathways A and B, and lots of suggestions have been proposed, as to which one of them that is correct. In pathway A the condensation of the substrate happens before the reduction step in which isopropanol is oxidized to acetone, whereas pathway B starts with the reduction.

The choice of reductant is likely to determine if the metal is reduced before or after the condensation. However, when an alcohol is used, pathway B seems to be more attractive. Dethlefsen and Fristrup[62] employed *in situ* IR spectroscopy to investigate the MTO catalyzed DODH of a 1,2-tetradecanediol by oxidation of 3-octanol. An increase in the reaction rate could be observed in the end of the experiments when most of the diol had been consumed. They reasoned that the substrate is trapping the Re catalyst as an unreactive $MeReO_2$(diolate) in an equilibrium state controlled by the concentration of diol (Scheme 14).



Scheme 14. Equilibrium state between the reactive $MeReO_3$ and unreactive $MeReO_2$(diolate).

The increased reaction rate towards the end of the experiments is thus a consequence of the concentration of substrate going down, which pushes the equilibrium towards the right hand side. The trapped Re catalyst will thus reenter the catalytic cycle and speed up the reaction. For this explanation to be true, the catalytic cycle must begin with the reduction step (Pathway B) because otherwise the trapping of the catalyst in the before mentioned equilibrium state would not be possible. Shiramizu and Toste[54] also concluded from their experiments that the alcohol driven DODH starts with the reduction step.

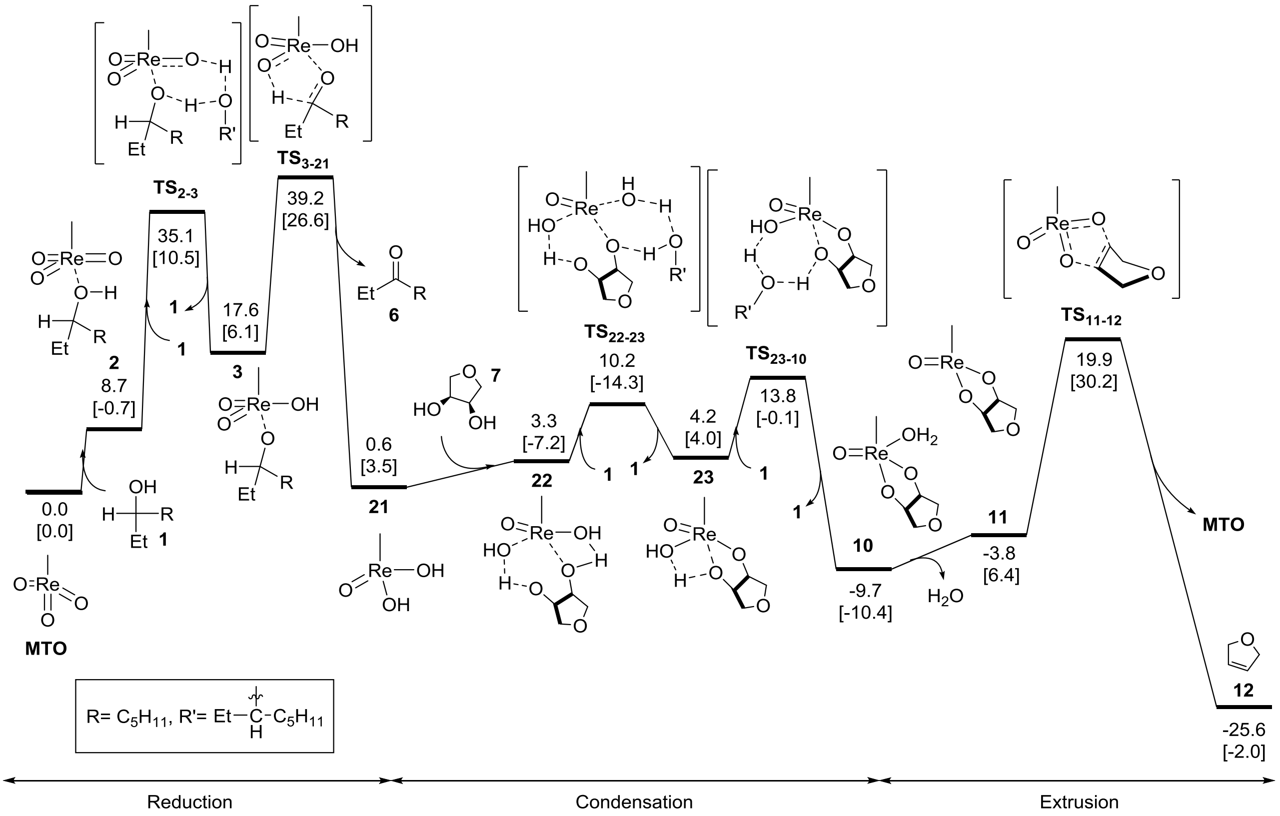


Figure 14. Calculated reaction pathway for DODH of 1,4-anhydroerythritol using MTO as catalyst and 3-octanol for reduction. Free energies and [enthalpies] are reported in kcal mol^{-1}.[63]

DFT calculations have been performed by Qu *et al.*[63] in order to study the reaction mechanism of MTO catalyzed DODH of 1,4-anhydroerythritol when using 3-octanol as the reductant (Figure 14). They found that the energy profile is more favorable for pathway B and that the alcohol is not only used for reduction of the metal center, but is also acting as a shuttle in the hydrogen-transfer steps throughout the mechanism. The extrusion step was found to be a concerted [3+2] retrocycloaddition in which the olefin is released and the catalyst regenerated. The DFT calculations also indicate that the reduction step is rate determining, though it is likely to depend on which reductant is employed. Experiments have shown that when using 3-octanol[D$_1$] isotopomers to reduce MTO in the DODH of 1,2-tetradecanediol, kinetic isotope effects (KIE) values of 2.1 and 1.1 is found for $C_5H_{11}CD(OH)C_2H_5$ and $C_5H_{11}CH(OD)C_2H_5$, respectively.[62] This underlines that the reduction step is rate determining and depending on cleavage of the C-H bond alpha to the hydroxyl group in the sacrificial alcohol.

The calculations by Qu *et al.*[63] also revealed that the reduced species is likely to be $CH_3ReO(OH)_2$ (no. 21 in Figure 14) rather than CH_3ReO_2L (Figure 13). However, both of the reduced Re compounds have been confirmed by experiments. The hydroxide complex was isolated

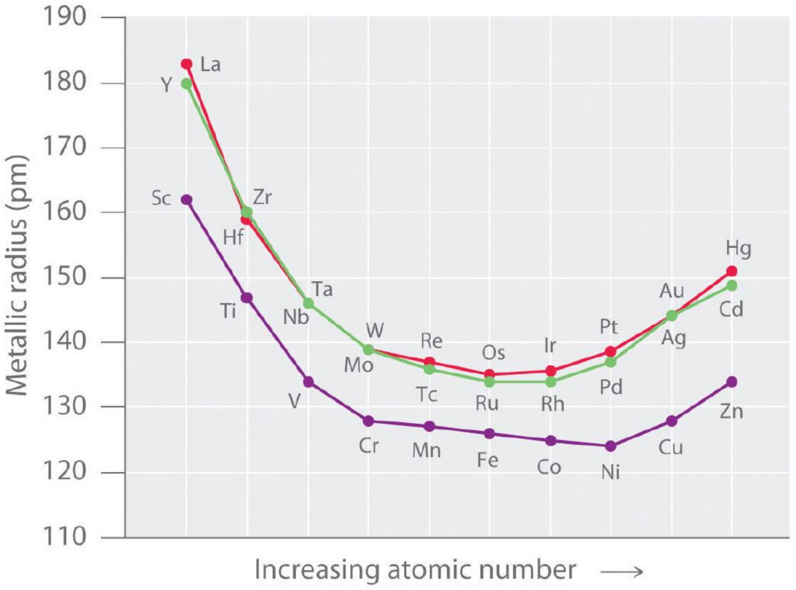


Figure 15. Metallic radius for the first, second and third row transition metals.[72]

by reaction of Tp´ReO_3 with PPh_3 in THF,[64] and the dioxo complex has been indirectly proven by coordination of 3-hexyne to give CH_3ReO_2(hexyne).[54]

2.1.1 Molybdenum and Vanadium DODH.

Because rhenium is a very expensive metal, it is interesting to look for cheaper alternatives. Molybdenum and vanadium are two good possibilities as their chemistry usually resemble that of rhenium, while the prices on the elements are lower (NH_4ReO_4: 1425; MoO_3: 13; V_2O_5: 9 \$ / kg).[71] One obvious similarity between these elements is found when comparing the atomic radius for the transition metals (Figure 15).[72] The size of V and Mo is roughly the same as for Re (and the other expensive metals usually implemented in catalytic systems) while the radius of the elements increases steeply when moving further towards the left hand side of the d-block. In the opposite direction however, reactivity goes down as the electronegativity increases and the elements become more noble in their character. Despite the size similarity, Mo and V also have a lot of possible oxidation states, just as Re does, which could be an important factor as the Re-catalyzed DODH process has been found to require a change of ±2 in oxidation.

The reaction mechanism for Mo and V has been investigated lately, and resembles the one outlined for Re-catalyzed DODH in Figure 13.[73,74] However, very resent calculations on vanadium have shown that the extrusion step is likely to be fundamentally different from the [3+2] retrocycloaddition in Re catalyzed DODH. Two individual research groups have performed DFT

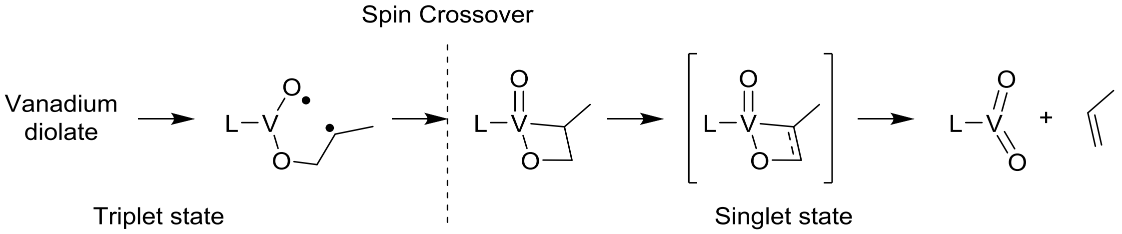


Figure 16. Extrusion step in the vanadium catalyzed DODH.

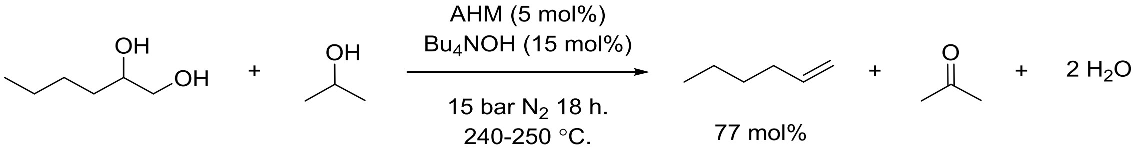
calculations on ethylene glycol[75] and 1,2-propanediol[76] when using the $[Bu_4N](dipic)VO_2$ catalyst. Both groups used PPh_3 for reduction and employed a solvation model for benzene in their calculations. Though the results do not agree on whether the reaction sequence is condensation, reduction, extrusion (pathway A) or the other way around (pathway B), both groups concluded that the extrusion step is a [2+2] retrocycloaddition from a metallacycle formed by a radical intermediate (Figure 16). The vanadium center is thus found to change spin state during the catalytic cycle, starting from a singlet configuration and then evolving into a triplet state that allows formation of the radical intermediate.

Since the first experiments employing Mo and V in non-polar solvents (Table 4, entry 1-3) demonstrated that efficient DODH may be obtained, resent publications have shown that under the right circumstances they may even become competitive to rhenium. Dethlefsen *et al.*[68] demonstrated that good yields of alkene from aliphatic diols could be obtained with the commercially available $(NH_4)_6Mo_7O_{24}•4H_2O$ (AHM), when tetrabutylammonium hydroxide (Bu_4NOH) is added to the reaction mixture. A yield of 77% 1-hexene was achieved this way from DODH of 1,2-hexanediol, with isopropanol acting both as solvent and reductant (Scheme 15).

Table 4. Historical Outline of the Scientific Developments of DODH Catalyzed by Inexpensive Metals.

	Year	Catalyst	Red.	Solv.	Substrate	°C	C=C Yield
1[65]	2013	$Mo(O)_2(HQ^{Cy})_2$	PPh_3	Toluene	1,2-Cyclooctanediol	110	55%
2[66]	2013	$[Bu_4N](dipic)VO_2$	PPh_3	Chlorobenzene	1,2-Tetradecanediol	170	97%
3[67]	2014	AHM	1,2-C_{14}diol	Dodecane	1,2-Tetradecanediol	220	43%
4[68]	2015	AHM + Bu_4NOH	2° alcohol	2° alcohol	1,2-Tetradecanediol	250	77%
5[69]	2016	Bis(phenolato)Mo	2° alcohol	2° alcohol	1,4-Anhydroerythritol	200	57%
6[70]	2016	$[Bu_4N](salhyd)VO_2$	CO	Chlorobenzene	1,2-Hexanediol	180	97%

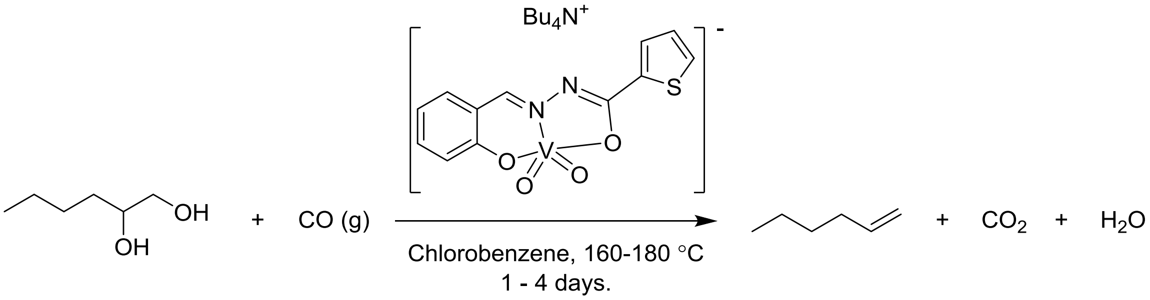
HQ^{Cy}= acylpyrazolone compound; dipic= dipicolinate; AHM= $(NH_4)_6Mo_7O_{24}•4H_2O$; salhyd= a salicylaldehyde hydrazide complex; bis(phenolato)Mo= Di(oxo){1,5-dithiapentanediyl-2,20-bis(4,6-di-tert-butylphenolato)}molybdenum, 1,2-C_{14}diol= 1,2-tetradecanediol.



Scheme 15. Deoxydehydration of 1,2-hexanediol with isopropanol acting as solvent and reductant. The reaction is catalyzed by $(NH_4)_6Mo_7O_{24}•4H_2O$ (AHM), which is aided by addition of Bu_4NOH.

Vanadium catalyzed DODH has also proven to be an interesting possibility. The $[Bu_4N](dipic)VO_2$ catalyst, developed by Nicholas and Chapman, is able to convert 1,2-octanediol into 1-octene in excellent yields, when conducted in chlorobenzene and PPh_3 is employed as the reductant.[66] Full conversion was reached after 48 hours at 150-170 °C, giving an alkene yield of 97% (Table 4, entry 2).

Later on, Nicholas and Gopaladasu[70] developed a system based on the V-complex $[Bu_4N](salhyd)VO_2$. They found that this vanadium species is able to use CO gas as the reductant for conversion of 1,2-hexanediol to give 97% 1-hexene at full conversion (Scheme 16; Table 4, entry 6). 1-Phenyl-1,2-ethanediol and ethyl tartrate could also be processed by the same procedure into styrene (48% yield at full conversion) and ethyl fumarate (67% yield, 80% conv.), respectively.



Scheme 16. Carbon monoxide used in the DODH of 1,2-hexanediol with $[Bu_4N](salhyd)VO_2$ as the catalyst.

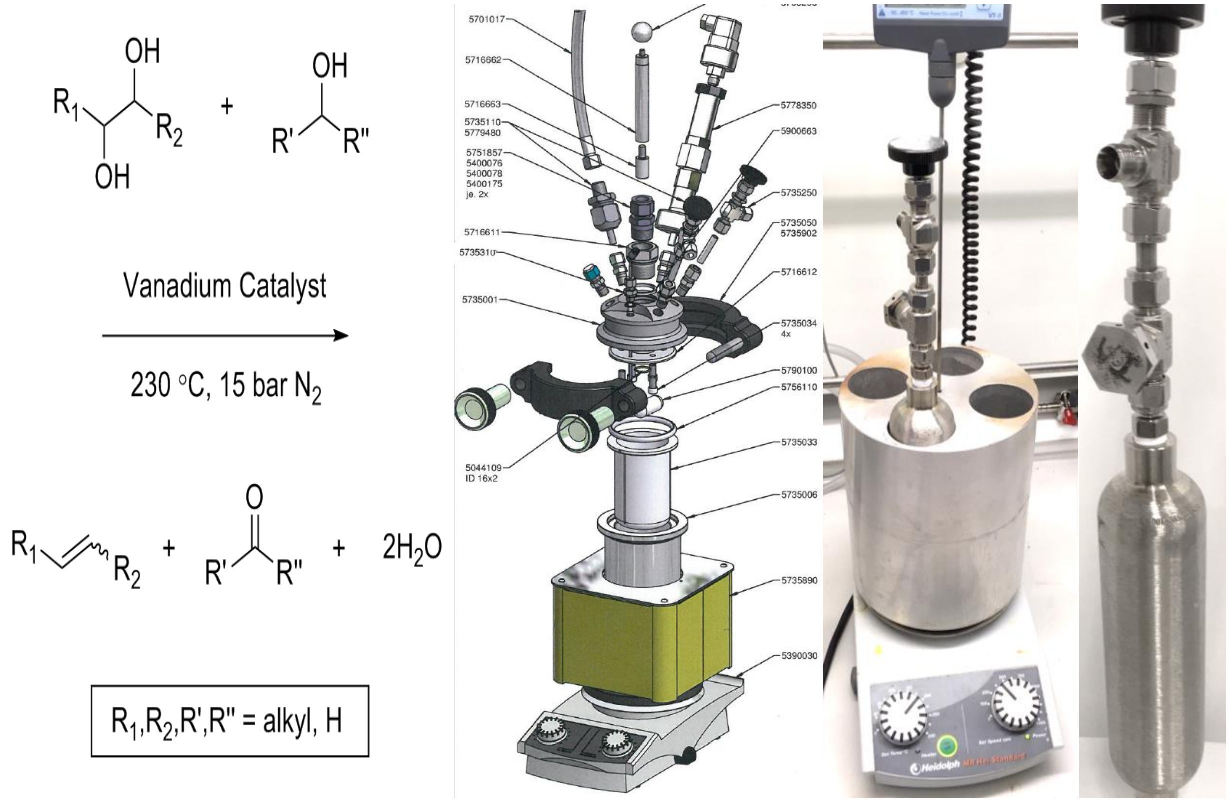
The following chapter will elucidate upon V-catalyzed DODH with an alcohol acting as both solvent and reductant.

2.2 Results

2.2.1 Initial Optimizations

The reaction setup and parameters were largely inspired by the Mo-catalyzed DODH, that we previously investigated.[68] The experiments were either conducted using an autoclave (reaction conditions A) or Swagelok cylinder (reaction conditions B), see Figure 17. As for Mo, V was found to favor the reaction at 230 °C, with a sharp decline in alkene yield at lower temperatures. To reach the high reaction temperature an initial starting pressure of 15 bar (usually nitrogen) had to be applied to the reaction vessel. The pressure would typically stabilize between 50 – 70 bar, in a standard experiment with *i*PrOH as solvent. More details on setup and reaction conditions are given in the experimental section, at the end of this chapter.

The preferred reaction time, substrate concentration and catalyst loading, was investigated, employing NH_4VO_3, 1,2-decanediol, and *i*PrOH as a combined solvent/reductant. This initial



Reaction to be investigated. Autoclave system. Swagelok system.

Figure 17. The reaction to be investigated and the equipment that have been used in most of the experiments.

Table 5. DODH of 1,2-Decanediol Catalyzed by 5 mol% NH_4VO_3 at Different Reaction Times. [a]

Time min. (hours)	Conv. [%]	Yields [%] of		
		C=C	C=O	1°OH
480 (8)	89	34	2	4
720 (12)	83	38	2	5
1000 (16½)	97	51	2	8
1020 (17)	100	50	3	9

Products: 1-decene (C=C), 2-decanone (C=O) and 1-decanol (1°OH).[a] Reaction conditions A were employed.

Table 6. DODH of 1,2-Hexanediol, Catalyzed by NH_4VO_3 at Different Concentrations. [a]

1,2-hexanediol (mmol/ml)	Conv. [%]	Yields [%] of		
		C=C	C=O	1°OH
0.2	93	43	0	7
0.3	93	46	4	7
0.4	94	48	4	6

Products: 1-hexene (C=C), 2-hexanone (C=O) and 1-hexanol (1°OH).[a] Reaction conditions B were employed.

system was chosen because it gave decent results with Mo and because all of the components are cheap and commercially available. The optimization of the reaction time is reported in Table 5 and complete conversion of 1,2-decanediol was not achieved until after 17 hours in the autoclave.

Concentration differences in initial substrate were found to give a very little increase in the final yield of alkene in favor of the more concentrated experiment (Table 6). It was therefore decided to use a substrate concentration of 0.4 mmol/ml for the entire investigation, to ensure a collection of comparable results. The influence of catalyst loading was also examined and 5 mol% catalyst was found to give the highest yield of alkene (Table 7). When the catalyst loading was increased, the yield of 1-hexene and 2-hexanone slowly declined. This could be caused by formation or precipitation of DODH unreactive polynuclear vanadium species in which the metal centers are bridged by substrate molecules.

Verification of the Experimental Procedure.

Deoxydehydration of 1,2-decanediol conducted using the autoclave (reaction conditions A) and Swagelok cylinders (reaction conditions B), was confirmed to give the same amount and types of products. However, a test experiment in the autoclave, with hexadecane (C_{16}), dodecane (C_{12}), heptane (C_7) and pentane (C_5), in 200 ml of *i*PrOH and heated to 230 °C for 12 hours, was

Table 7. DODH of 1,2-Hexanediol Catalyzed by Different Amounts of NH_4VO_3. [a]

NH_4VO_3 (mol%)	Conv. [%]	Yields [%] of		
		C=C	C=O	1°OH
1	58	31	3	4
3	69	36	6	5
5	94	48	4	6
10	100	45	4	7
20	100	41	3	7

Products: 1-hexene (C=C), 2-hexanone (C=O) and 1-hexanol (1°OH).[a] Reaction conditions B were employed.

conducted. Comparison of the GC areas before and after the experiment concluded that the C_{16} and C_{12} hydrocarbons do not leak out, whereas the areas for the shorter C_7 and C_5 carbons were reduced by 10% and 38%, respectively. The cylinders however, could be sealed much better and addition of 2-methylpentane to several experiments generally showed that only 1 – 5 mol% of the added hydrocarbon escapes the reaction vessel.

How well the cylinders could be sealed, was also apparent in an experiment made to clarify whether significant reverse reaction (dihydroxylation) of the produced alkene could take place. 1-hexene (10 mmol), acetone (10 mmol), and H_2O (20 mmol) were mixed in *i*PrOH and the sample analyzed after heating to 240 - 250 °C for 16.5 hours. 94% of the initial 1-hexene was recovered, which means that there are no significant reactions to remove the alkene once it is formed, unless the alkene can react with the diol substrate.

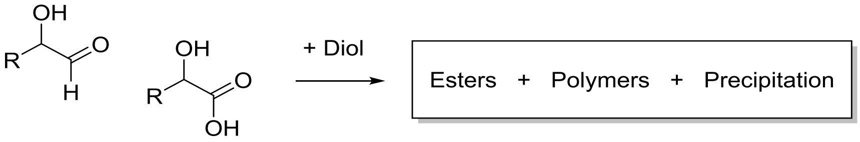
Table 8. Test of H_2 and CO as Reductants in the DODH of 1,2-Decanediol Using NH_4VO_3 as Catalyst.[a]

Gas	Solvent	Conv. [%]	Yields [%] of			
			C=C	C=O	2°OH	1°OH
H_2 [b]	hexane	Full	32	6	1	1
N_2	hexane	Full	30	9	3	3
H_2 [b]	*i*PrOH	93	48	2	2	6
N_2	*i*PrOH	91	51	2	1	8
CO [c]	*i*PrOH	Full	51	2	1	5

Products: 1-decene (C=C), 2-decanone (C=O), 2-decanol (2°OH) and 1-decanol (1°OH). [a] Reaction conditions A. Reaction time: 1000 min. [b] Experiments conducted by Johannes R. Dethlefsen. [c] The pressure of CO was 14 bar (approx. 113 mmol).

2.2.2 Solvents and Reductants

The best reductants in terms of price, sustainability, and atom economy are H_2 and CO. They were tested and found to yield almost identical product distributions and yields, as when the DODH reaction was done under N_2 gas (Table 8). The tests were performed in both *i*PrOH and hexane. Isopropanol was chosen because it is a polar solvent able to dissolve most oxygen rich compounds. However, oxidation of this solvent could be competitive to oxidation of the applied gasses. Hexane was therefore tested as well, because it cannot get oxidized, and the experiment should therefore clarify whether the applied gaseous reductants were working as intended. It was not the case, as the reaction in hexane and under inert N_2 gas, resulted in 30% alkene yield as well (Figure 18). This result means that the diol substrate must play a dual role in which it is either reduced to the alkene or oxidized in order to reduce the catalyst, as has been found for Mo-catalyzed DODH.[67] Several attempts using GC, GCMS, LCMS, NMR and diols with shorter carbon chains, have been unsuccessful in discovering what happens to the rest of the substrate. The missing oxidation products could be the 2-hydroxy acids or aldehydes, obtained when the primary hydroxyl group in the diol is oxidized. The acids or aldehydes may then undergo further reactions into 2-hydroxy esters or form polymers that precipitates from the mixture (Scheme 17). In experiments on 1,2-hexanediol, with *i*PrOH as the solvent, isopropyl 2-hydroxyhexanoate has been found to be a minor



Scheme 17. 2-Hydroxy species responsible for the missing oxidation products when DODH is performed in hexane.

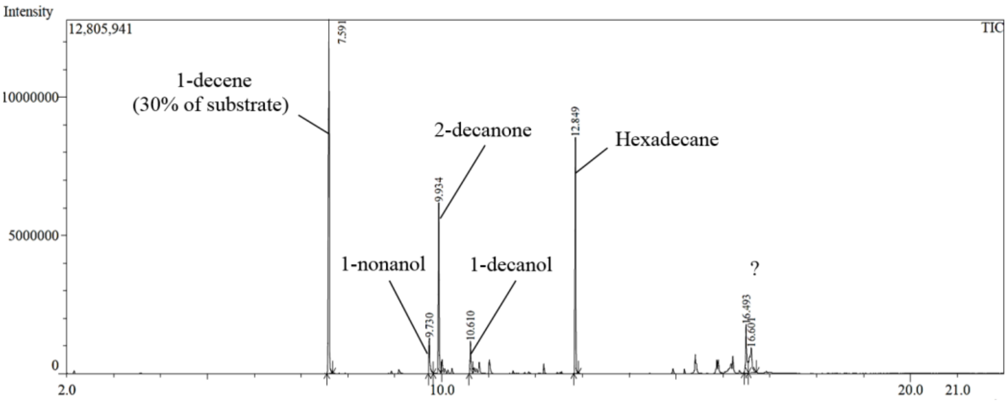


Figure 18. GCMS spectrum after reaction of 1,2-decanediol, in hexane, and under inert N_2 gas.

Table 9. Comparison of Organic Solvents in the NH_4VO_3 Catalyzed DODH of 1,2-Decanediol.[a]

Solvent	Conv. [%]	Yields [%] of			
		C=C	C=O	2°OH	1°OH
MeOH	35	6	1	1	1
EtOH	64	17	4	1	3
*n*PrOH	78	27	2	1	3
*i*PrOH	97	51	2	1	8
3-Pentanol	97	46	2	1	6
2,2,2-trifluoroethanol [b]	67	19	0	0	3
Hexafluoroisopropanol [b]	61	13	0	0	4
2,4-Dimethyl-3-pentanol [c]	full	45	10	0	7
Cyclohexanol	98	43	2	2	5

Products: 1-decene (C=C), 2-decanone (C=O), 2-decanol (2°OH) and 1-decanol (1°OH). [a] Reaction conditions A. Reaction time: 1000 min. [b] Reaction conditions B; the substrate was 1,2-hexanediol and 1-heptanol was used as the internal reference. [c] Reaction conditions B; The substrate was 1,2-hexanediol.

side product (*vide infra*). If oxidation of one of the hydroxyl groups in the diol substrate drives the reaction, then that would lower the theoretical yield of reduced species to 50%.

Recently published experiments, have shown that when the catalyst $[Bu_4N](salhyd)VO_2$ (salhyd = salicylaldehyde hydrazide) is used in benzene or chlorobenzene, then CO gas can be an effective reducing agent.[70] A polar solvent would be a better choice, but when the DODH is conducted in *i*PrOH and with NH_4VO_3 as the catalyst, then neither H_2 nor CO gas seems to work. Therefore, a decision was made to explore the alcohol-driven DODH. The alcohol that is used, may both function as solvent and reductant which simplifies the reaction protocol. Oxidation of the alcohol will lead to ketones or aldehydes, that may afterwards be recycled by hydrogenation techniques. Table 9 summarizes the results obtained from DODH of 1,2-decanediol in a range of different alcohols. The primary alcohols tend to give low conversion of the diol substrate, though better yields are achieved when the length of the aliphatic carbon backbone is prolonged. The secondary ones however, are more prone to facilitate efficient deoxydehydration. The preference for the secondary alcohols is also seen in Mo-catalyzed DODH,[68] and even the more reactive Re adopt this tendency.[54]

Both *i*PrOH and 3-pentanol gave good yields of the corresponding alkene (50%). These are encouraging results, as further commercialization may become easier if the alcohol is produced in a cheap and green fashion. The production of *i*PrOH is either done by hydration of propene or hydrogenation of acetone.[77] Especially the source from acetone may become interesting, as it is produced in the acetone-butanol-ethanol (ABE) fermentation of a wide range of carbohydrates derived from biomass.[78] Huge amounts of acetone is also produced industrially by the cumene route to obtain phenol, which keeps the price on acetone very low.[79] Hydrogenation of 3-pentanone to 3-pentanol is also possible, but there are not as many ways to generate 3-pentanone as there are to generate acetone. In the view of renewability, price, and solubility properties, *i*PrOH was selected as the solvent for most of the experiments.

It was decided to test the fluorinated versions of isopropanol and ethanol, to gain more insight into which properties that determine the DODH ability of the alcohol. Addition of the electrophilic fluorine atoms resulted in lower conversion and alkene yield. These solvents seem to generally render the catalyst less reactive, contrary to the experiment in hexane where full conversion was achieved. This observation suggests that the lowered reactivity is due to strong interactions between the unreactive fluorinated alcohols and vanadium, which shields the catalyst from reacting with the substrate. The results also indicate that the electron-poor fluorinated alcohols are harder to oxidize than the more electron-rich isopropanol.

In order to test a secondary alcohol with electron donating, or at least sterically demanding methyl groups, 2,4-dimethyl-3-pentanol was evaluated. This solvent has already proven to be a good reductant in rhenium-catalyzed DODH of glycerol,[80] and 1-phenyl-1,2-ethanediol.[53] Only modest alkene yields were detected however, just as previously reported for vanadium DODH in benzene with 2,4-dimethyl-3-pentanol as the reducing agent.[66] Cyclohexanol was tested for the same reasons, but it did not improve the DODH activity and only a small amount of cyclohexanone was found.

Benzyl alcohol was added as a possible reductant (80 mmol) to NH_4VO_3 (2.7 mol%), but was found to undergo transfer hydrodeoxygenation (HDO) instead of oxidation to benzaldehyde. Toluene, which is the main product formed by HDO, was found in 37% yield when the reaction was performed in *i*PrOH (100 ml in the autoclave). The same experiment was also done in ethanol to give 30% toluene. This HDO reaction of benzyl alcohol has also been observed with molybdenum, and an investigation has recently been published on the matter.[40] A test experiment with 1,2-decanediol and benzyl alcohol in hexane, gave only a minor alkene yield probably due to the aforementioned oxidation of the diol.

Indoline, which has proven to be a strong reductant in Re mediated DODH, was also tested.[59] A Swagelok cylinder was charged with 1,2-hexanediol and 1 equivalent of indoline in 50 ml *i*PrOH, according to reaction conditions B. This experiment resulted in 43% yield of 1-hexene, along with a total conversion of the substrate.

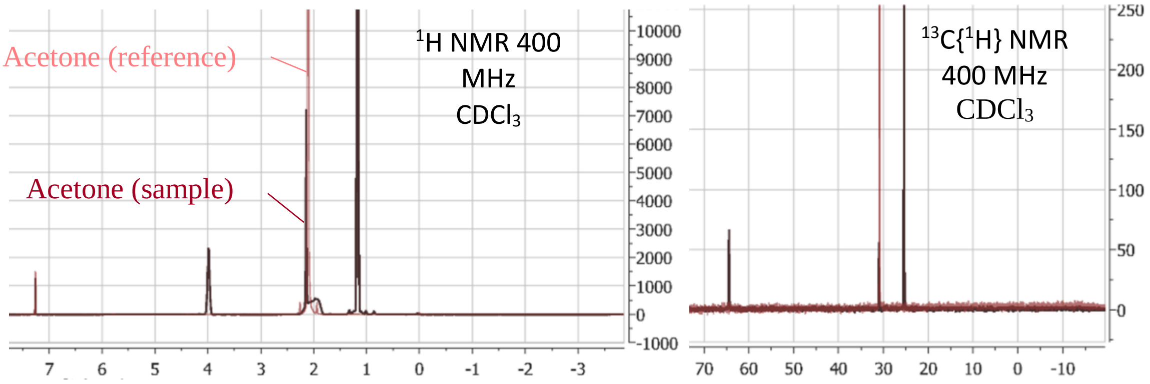


Figure 19. Detection of acetone by ^{1}H and ^{13}C{^{1}H} NMR, in CDCl$_3$, after reaction of 1,2-decanediol in *i*PrOH.

At this point it seems appropriate to consider if the reaction is using the *i*PrOH for reduction, or if it prefers to sacrifice the diol. A test experiment was performed on 1,2-decanediol, under reaction conditions B. The resulting mixture was distilled with care, to up-concentrate the acetone within the isopropanol. Then the distillate was analyzed by NMR spectroscopy and acetone detected as a singlet at 2.14 ppm (Figure 19). Another indication of *i*PrOH acting as the reducing agent, is the fact that the total amount of reduced species (Table 9: C=C 51%, 2°OH 1%, 1°OH 8%) in the sample constitutes 60% of the initial substrate. Oxidation of the diol alone is not sufficient to reach this amount, unless the substrate is doubly oxidized which would allow for 66% alkene yield. Even though there is only weak evidence for oxidation of the solvent, chances are that it is a combination of both diol and *i*PrOH that act as reductants. The challenge is therefore to make changes to the vanadium catalyst, so that it facilitates oxidation of the solvent rather than the diol.

2.2.3 Vanadium Catalysts

Synthesis of vanadium complexes was limited to those that are easy to make and likely to stay coordinated to the vanadium center at 230 °C, because the high reaction temperature is likely to cause rapid exchange of the ligands. For this reason, test of different commercially available catalysts seemed to be the best approach. A range of different vanadium complexes in oxidation states III, IV, and V, were tested for their activity towards DODH of 1,2-decanediol (Table 10). These are the most common oxidation states of vanadium, with V meaning the total removal of all [Ar]3d^{3}4s^2 valence electrons from the atom. The survey showed that almost all the tested vanadium catalysts are able to catalyze the reaction and with most alkene yields around 50%. That also goes

Table 10. Comparison of different vanadium catalysts for DODH of 1,2-decanediol.[a]

Ox. state	Catalyst	Conv. [%]	Yields [%] of			
			C=C	C=O	2°OH	1°OH
V	$Bu_4N[VO_2(dipic)]$ [b]	95	47	2	1	7
V	NH_4VO_3	97	51	2	1	8
V	V_2O_5	93	47	2	1	8
V	$VO(isopropoxide)_3$	92	48	2	1	8
IV	$VO(acac)_2$	Full	54	4	2	10
III	$V(acac)_3$	94	50	2	1	7
V	$(Bu_4N)_3[V_{10}O_{28}H_3]$ [g]	92	23	6	0	19
V	NH_4VO_3 + acid [c]	93	50	2	1	7
V	NH_4VO_3 + base [d]	87	40	2	1	5
V	$(Bu_4N)_3[V_{10}O_{28}H_3]$ + base [e]	91	50	3	0	5
IV	$VOSO_4 \cdot xH_2O$	77	2	1	9	7
V	Na_3VO_4	37	1	1	0	1
IV	VO(tpp) [f]	84	18	5	0	16

Products: 1-decene (C=C), 2-decanone (C=O), 2-decanol (2°OH) and 1-decanol (1°OH). [a] Reaction conditions A. Reaction time: 1000 min. [b] 4.5 mol% catalyst. [c] 1.2 equivalent of acetic acid to catalyst. [d] 3 equivalent of *n*-Bu_4NOH to catalyst. [e] Reaction conditions B. 3 equivalent of *n*-Bu_4NOH to catalyst was used and the substrate was 1,2-hexanediol. [f] Reaction conditions B. 1,2-hexanediol used as substrate. 4 mol% catalyst was used and the reaction time was 990 min. tpp = 5,10,15,20-tetraphenylporphyrine ligand. [g] Reaction conditions B. 1,2-hexanediol used as substrate. The reaction time was 1260 min.

for the $Bu_4N[VO_2(dipic)]$ catalyst, which give excellent results for DODH in chlorobenzene and with PPh_3 as reductant (Table 4, entry 2).[66]

The vanadium salts NH_4VO_3, $Bu_4N[VO_2(dipic)]$ gave good conversion and yields, unlike Na_3VO_4, and $VOSO_4 \cdot xH_2O$. The biggest difference is found in the solubility, since the latter two compounds are known to be highly soluble in water and insoluble in alcohols, whereas the former are soluble in alcohols. Thus, it seems important to choose a vanadium species that is slightly soluble in *i*PrOH from the beginning. V_2O_5, gave good yields as well, and is also known to be insoluble in H_2O, but soluble in ethanol.

$VO(isopropoxide)_3$, $VO(acac)_2$, $V(acac)_3$ were tested because they are all soluble in *i*PrOH and span the three most common oxidation states of the metal. Although very little difference was found between the three, it should be mentioned that the V(IV) compound performed better than any other catalysts tested (54% yield of alkene). It is however unlikely that this species returns to oxidation state IV during the catalytic cycle, as the DODH process requires a change of ±2. A vanadium(VI) complex cannot be formed as it depends upon the removal of more than just the valence electrons from the atom, also vanadium(II) complexes are usually very unstable. The most likely oxidation

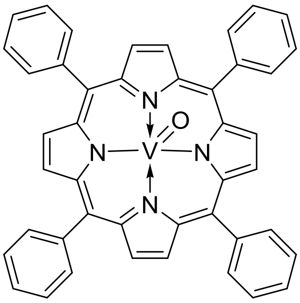


Figure 20. 5,10,15,20-Tetraphenyl-21H,23H-porphine vanadium(IV) oxide.

states to be involved in vanadium catalyzed DODH is therefore thought to be (III) and (V). Why the yield is higher when $VO(acac)_2$ is used as the catalyst is unclear, but it could be a consequence of faster initiation of the catalyst to form a DODH active vanadium (III) or (V) complexes.

The ligand 5,10,15,20-tetraphenyl-21H,23H-porphyrine (tpp) on the vanadium(IV) complex abbreviated VO(tpp), was also investigated (Figure 20). A literature search on V-tpp compounds, solely resulted in vanadium(IV) species. Just a small amount of 1-hexene was obtained in the experiment (18%), which is in line with the discussion above that V(IV) compounds cannot take part in the catalytic cycle. The low deoxydehydration activity, that is observed anyway, is probably because some of the VO(tpp) is converted into DODH active vanadium (III) or (V) diolates.

The tetrabutylammonium polymetalate[81], $(Bu_4N)_3[V_{10}O_{28}H_3]$ in Figure 21, was found to give a low yield of alkene (23%). This was ascribed to a slow transformation of the complex into vanadium-oxo species that catalyze the DODH reaction. Addition of the base, tetrabutylammonium hydroxide, (n-Bu_4NOH) to the polymetalate improved the yield of 1-hexene to 50%. The same happened when the base was added in Mo-catalyzed DODH using $(NH_4)_6Mo_7O_{24}\cdot 4H_2O$ as the catalyst. In that case, the yield of 1-hexene increased from 46 to 77% when n-Bu_4NOH was

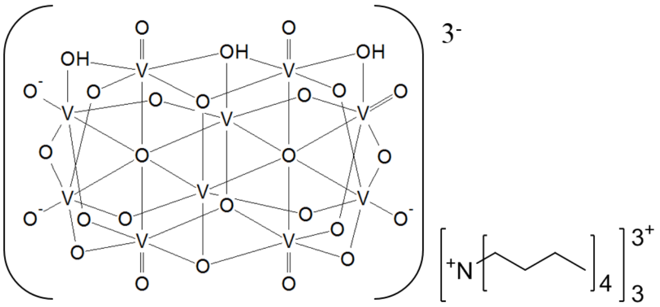


Figure 21. The tetrabutylammonium polymetalate $(Bu_4N)_3[V_{10}O_{28}H_3]$.

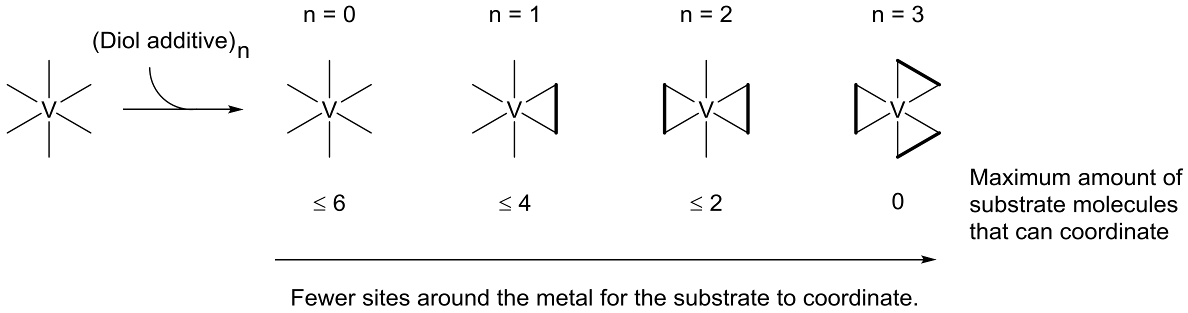


Figure 22. Addition of an additive that cannot undergo DODH itself. The amount of additive that binds to vanadium, controls the maximum amount of substrate molecules that may coordinate.

added.[68] The most likely reason for this behavior is that base help to split up the metalate, just by being nucleophilic, thus leading to species that catalyze the deoxydehydration reaction more efficiently. A negative effect is observed when *n*-Bu_4NOH is added to NH_4VO_3, likely because the catalyst is already monomeric in solution, thus the base is just inhibiting the metal which leads to less alkene production.

Acetic acid was also tested, because it is organic and not as strong as the mineral acids. Addition of a strong acid to the reaction mixture could damage the equipment and was therefore avoided. However, adding acetic acid to NH_4VO_3 gave no differences in the resulting product yields and this approach was therefore abandoned.

2.2.4 Additives Containing the Diol Functionality

It was considered that the products, and their distribution, may depend upon the amount of substrate molecules that can coordinate to the metal center at the same time. In order to investigate this, different bidentate additives was added to the reaction mixture with the aim of blocking some of the possible coordination sites that the vanadium center may have (Figure 22). A perfect additive should therefore bind irreversibly to the vanadium center and be non-susceptible to undergo any other reactions itself. This lead to an investigation of additives containing the diol moiety on an aromatic backbone, as they cannot deoxydehydrate. Only very few groups have tried to characterize vanadium diolates, because it is hard to grow crystals of sufficient quality for X-Ray crystallography. The structures in solution often differ a lot from the structure of the crystallized catalyst and most of the data is thus based on IR and NMR.[82,83] However, Crans *et al.*[82] came to the conclusion that complexes of *trans*-1,2-cyclohexanediol, (±)-2,3-butanediol, (2*R*,3*R*)-2,3-

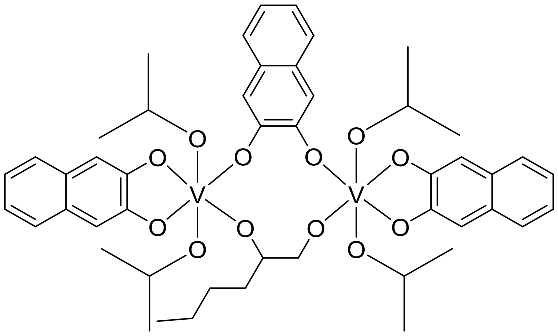


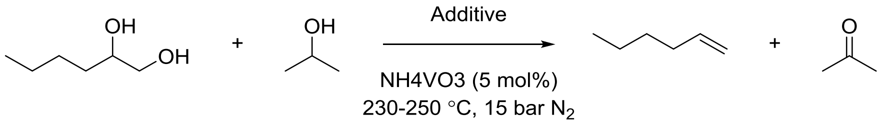
Figure 23. Possible structure of a dimeric vanadium compound responsible for the increased yield of 1-hexanol, when 1.5 equivalent of 2,3-dihydroxynaphthalene to V was added.

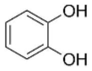
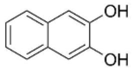
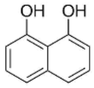
butanediol, and ethylene glycol, all form complexes with six-coordinated vanadium centers. It is therefore likely that the tested additives will also facilitate vanadium with six coordination sites.

Catechol was found to block the reaction of 1,2-hexanediol, though an increase in the yield of 1-hexanol was observed when 1.5 equivalent of catechol was added from the beginning (Table 11). A more pronounced increase in the primary alcohol was found when the additive was 2,3-dihydroxynaphthalene. Changing the concentration of the additive, gave a peak in the outcome of 1-hexanol (26%), when 1.5 equivalent of additive to V was used. A dimeric vanadium complex, where two molecules of the additive is bridging between the vanadium centers, seems unlikely because the amount of formed 1-hexanol peaks at 1.5 equivalent of 2,3-dihydroxanapthalene to V. It may however be a system in which two vanadium atoms are connected by one molecule of the additive, and one of the diol substrate as depicted in Figure 23. A test with 1.5 equivalent of 2,3-dihydroxynapthalene at 200 °C was also performed to check if the process that forms the primary alcohol can happen at a lower temperature than 230 °C, but it showed no conversion of the diol.

3-Fluorocatechol, and especially tetrafluorocatechol, lowered the overall conversion of substrate already at very small additive to vanadium ratios. Just 1.5 equivalent of tetrafluorocatechol was enough to completely stop any reaction from happening. The aromatic ring may be so electron deficient that it lowers the overall reactivity of the metal and it must bind very strongly since it is able to do it at this low concentration. The test in which 0.75 equivalent of tetrafluorocatechol to V was added, gave almost a 1:1 ratio between conversion and yield of 1-hexene (Table 11). A long time experiment (72 h) was therefore performed, but the amount of 1-hexene (40%) was not equimolar to the conversion (61%) anymore.

Table 11. Test of Different Additives to NH_4VO_3 Catalyzed DODH of 1,2-Hexanediol. [a]

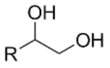
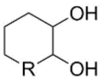
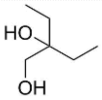
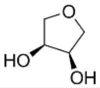
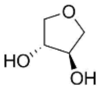
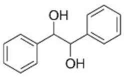
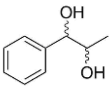
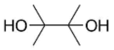


Additive	Eqiv		Conv. [%]	Yields [%] of		
				C=C	C=O	1°OH
 Catechol	1.5		64	24	3	15
	10		42	7	0	8
3-Fluorocatechol	2		31	11	0	8
	10		10	3	0	2
Tetrafluorocatechol	0.5		46	31	0	2
	0.5	72 h	92	52	3	7
	0.75		17	18	0	0
	0.75	72 h	61	40	0	5
	1		21	17	0	0
	1.5		0	5	0	0
 2,3-Dihydroxynaphthalene	0.5		88	32	3	17
	1		67	18	3	21
	1.5		70	15	2	26
	1.5	200 °C	0	2	0	0
	2		63	15	2	18
	2.5		50	6	0	17
	10		37	3	0	3
2,3-Naphthalenediamine	0.5		94	50	3	6
	1		95	51	4	7
	1.5		95	50	4	6
	3		96	49	4	6
 1,8-Dihydroxynaphthalene	0.56		93	47	0	8
	1		91	41	0	9
	1.5		45	19	2	6
	2		24	12	0	3
	10		0	0	0	0
1,8-Naphthalenediamine	1		94	48	3	5
	1.5		91	47	2	5
1,2,3-trihydroxybenzene	1.5		9	5	0	3

Products: 1-hexene (C=C), 2-hexanone (C=O) and 1-hexanol (1°OH). [a] Reaction conditions B.

When 1,8-dihydroxynapthalene was used, the conversion and yield of all products declined as the amount of additive was increased. Why addition of this compound do not give rise to more 1-hexanol is unknown, unless it is unable to bridge between the two metal centers in Figure 23. When the nitrogen analogues of the two tested dihydroxynapthalene compounds were tested, the DODH of 1-hexene proceeded as if no additive had been added. Oxygen based ligands are therefore likely

Table 12. Comparison of Different Substrates in NH_4VO_3 Catalyzed DODH.[a]

Substrate		Conv. [%]	Yields [%] of
			C=C
	1,2-Hexanediol	86, 94	41, 48
	1,2-Decanediol	95, 100	51, 50
	*trans*-1,2-Cyclohexanediol[b]	18, 14	5, 5
	cis-1,2-Cyclohexanediol[b]	4, 3	1, 1
	cis-1,2-Cyclooctanediol	23, 35	3, 5
	2-Ethyl-1,2-butanediol	Full	9, 10
	1,4-Anhydroerythritol	9	9
	1,4-Anhydrothreitol	0	0
	(*R*,*R*)-Hydrobenzoin	Full	16 (*trans*)
	meso-Hydrobenzoin	Full	30 (*trans*)
	*rac*-1-Phenyl-1,2-propanediol	Full	3/37 (*cis*/*trans*)
	Pinacol	Full	30%

Some of the experiments were conducted two times, to check the reproducibility of the results. [a] Reaction conditions B were employed. [b] Reaction time was 990 min.

to coordinate more strongly than their nitrogen counterparts. Lastly, the 1,2,3-trihydroxybenzene additive was tested to see if the extra hydroxyl group could make a difference to the reactivity of the resulting V-catalyst. Only low conversions and yields were achieved however.

Though addition of small amounts of an additive to NH_4VO_3 can make changes to the ongoing reaction, none of the attempts have been successful in improving the 50% alkene yield threshold that is encountered. Attention was therefore moved to other substrates than the straight chain 1,2-diols tested so far, to hopefully gain information about unknown byproducts and selectivity issues.

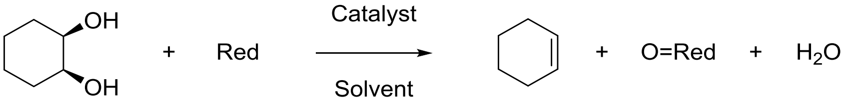
2.2.5 Substrates

When changing from 1,2-hexanediol and 1,2-decanediol (both giving alkene yields of roughly 50%), to substrates where both of the hydroxyl groups are secondary, the conversion and amount of products declines dramatically. Reactions employing either *cis*- or *trans*-cyclohexanediol resulted in yields of only 1% and 5% of cyclohexene, respectively (Table 12).

Mo-catalyzed DODH is however able to convert 29% of *cis*-1,2-cyclohexanediol to cyclohexene (Table 13) and 14% of the *trans* stereoisomer under similar conditions to those employed for V.[68] The two substrates have also been scrutinized with Re as the catalyst. In benzene, CH_3ReO_3 catalyzed DODH is able to convert *cis*-1,2-cyclohexanediol to cyclohexene in 15% yield when using 5-nonanol as reductant,[84] and 25% yield when using Na_2SO_3.[53] With 3-octanol as both solvent and reductant the *cis* isomer has been found to form cyclohexene in 72% yield when 2.5 mol% $Re(CO)_5Br$ is heated to 170 °C.[52] Employing H_2 to reduce CH_3ReO_3 was found to convert *cis*-1,2-cyclohexanediol to the alkene in 60% yield when heated to 150 °C in THF, for 8 hours.[50] *trans*-1,2-Cyclohexanediol however, does not react in any of the Re-mediated systems reported above, which clearly illustrate the importance of the *cis* configuration.[53,52]

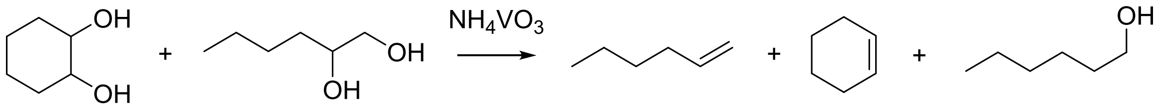
The results obtained for *cis*- and *trans*-1,2-cyclohexanediol show that the *cis* stereo configuration is more reactive towards DODH than the *trans* isomer. The deoxydehydration reactions for V,[74] Mo,[68] and Re[63,85] are all expected to go through a diolate complex in which both hydroxyl groups coordinate to the metal center simultaneously. The different orientations of the OH groups in the *trans* stereoisomer of 1,2-cyclohexanediol may obstruct formation of such a diolate complex and thereby impede the reaction. Vanadium however, is generally very selective towards vicinal diols with exactly one primary alcohol group, thus low conversion of both the *cis* and *trans* stereoisomers of 1,2-cyclohexanediol was found. Two experiments that clearly show the importance of the

Table 13. The DODH of *cis*-1,2-Cyclohexanediol Using V, Mo and Re Catalysts.



Catalyst		Reductant (red)	Solvent	Temp. [°C]	Time [h.]	Yield [mol%]
NH_4VO_3	5 mol%	*i*PrOH	*i*PrOH	250	17	1
AHM [a]	5 mol%	*i*PrOH	*i*PrOH	250	17	29
$Re(CO)_5Br$	2.5 mol%	3-Octanol	3-Octanol	170	3	72
CH_3ReO_3	10 mol%	5-Nonanol	Benzene	140	67	15
CH_3ReO_3	10 mol%	Na_2SO_3	Benzene	160	48	25
CH_3ReO_3	5 mol%	300 psi H_2	THF	150	8	60

[a] $(NH_4)_6Mo_7O_{24}•4H_2O$.

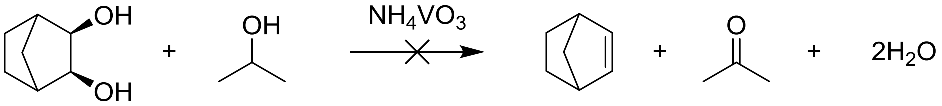


cis-1,2-hexanediol	19%	3%	4%
trans-1,2-hexanediol	43%	4%	10%

Scheme 18. The influence by differently oriented hydroxyl groups.

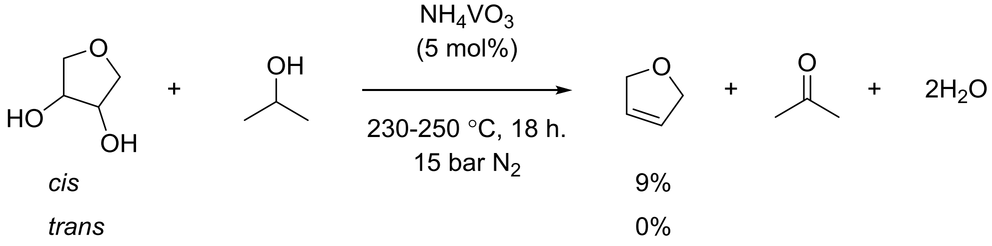
orientation of the two hydroxyl groups are depicted in Scheme 18. In these experiments the DODH of 1,2-hexanediol was conducted in the presence of either *cis*- or *trans*-1,2-cyclohexanediol. The yield of 1-hexene was dramatically lowered when *cis*-1,2-cyclohexanediol was added (50% to 19%), whereas the *trans* isomer imposes a much smaller change in the alkene yield. A likely explanation for this behavior, is that *trans*-1,2-cyclohexanediol cannot form a vanadium diolate under the reaction conditions. The *cis* isomer however, is a much better ligand and thus competes with the substrate for the vanadium center, which is reflected in the low yield of alkene. *trans*-1,2-Cyclohexanediol may however, function as a bridge between two vanadium centers as has also been reported in literature.[82] For this reason, the difference in the yield of 1-hexanol between the experiments with added *trans*- and *cis*-1,2-cyclohexanediol (10% and 4% respectively) once again indicate that the vanadium compound leading to the primary alcohol is binuclear.[82]

cis-1,2-Cyclooctanediol was investigated to see if a larger and more flexible ring system facilitates the DODH reaction better than the six membered counterparts. Although the two supposedly identical experiments, gave different conversions (23 and 35%), the yield of alkene was generally low (3% and 5% in Table 12). To test the influence of a more strained ring system, it was decided to synthesize the bridged *cis*-2,3-norbornanediol. This diol however, gave no yield of norbornene probably due to the strained double bond that would have to form (Scheme 19). Studies of Re-catalyzed dihydroxylation of alkenes (reverse DODH) have shown that the more strained alkenes are easier to oxidize to the corresponding diols,[86,87] which could also be true for vanadium.



Scheme 19. *cis*-2,3-Norbornanediol was found unable to undergo V-catalyzed DODH.

1,4-Anhydroerythritol, which is the dehydration product of erythritol and thereby related to biomass, was also investigated. This substrate resulted in only 9% 2,5-dihydrofuran at 9% conversion after 17 hours, whereas the *trans* isomer of the molecule (1,4-anhydrothreitol) did not react at all (Scheme 20). A very low yield was also found for the straight chain 3,4-hexanediol, contrary to what has been observed with rhenium and molybdenum.



Scheme 20. V-catalyzed DODH was found to work very poorly with 1,4-anhydroerythritol.

The apparent selectivity of the vanadium catalyst towards vicinal diols containing at least one terminal hydroxyl group, called for a broader survey of some more reactive substrates that do not have a primary and a secondary alcohol group. A very small amount of 2-ethyl-1-butene (10%) was achieved from DODH of 2-ethyl-1,2-butanediol. Instead, 50% of the substrate was deoxygenated at the tertiary carbon to form 2-ethyl-1-butanol. Formation of the double bond in 2-ethyl-1-butene should, promote DODH of 2-ethyl-1,2-butanediol over 1,2-hexanediol, because substituted double bonds are known to be energetically more favorable. However, the DODH of this compound is clearly being outcompeted

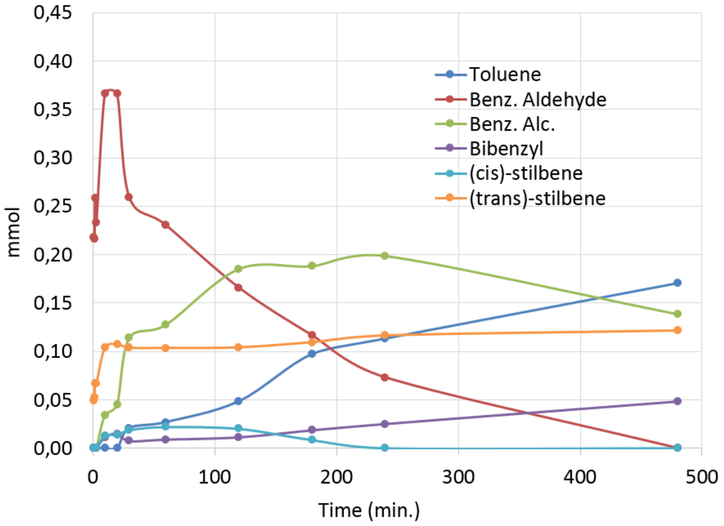


Figure 24. Time resolved experiment of hydrobenzoin (both diastereoisomers) conducted in a microwave at 230-250 °C.

by deoxygenation of the tertiary hydroxyl group.

Two diastereoisomers of hydrobenzoin (*meso* and *R*,*R*) have also been inspected (Table 12). The stilbene products should be stabilized by conjugation with the aromatic rings and therefore promote the DODH process of this substrate. Both of the isomers yielded *trans*-stilbene almost exclusively, and a test experiment showed that thermal isomerization from *cis* to *trans* cannot explain it alone. However, DFT calculations by Daniel Larsen, have revealed that the V-catalyzed DODH reaction sequentially breaks the C-O bonds which allow rotation around the centered C-C atoms.[88] Some distinct byproducts were also observed. Besides *trans*-stilbene the experiments on hydrobenzoin also yielded benzyl alcohol, toluene and bibenzyl. Because of the products formed, the DODH of hydrobenzoin is apparently different from that of the other tested substrates for which no products related to cleavage of the diol were found.

Microwave experiments were conducted on mixtures of both diastereoisomers of hydrobenzoin (0.5 mmol), in 3-pentanol, at different timespans, and catalyzed by NH_4VO_3. The experiments however, were complicated by unexpected explosions of the reaction vessel, which could not be explained by the pressure alone. A theory is that the catalyst deposits and cause a rapid local heating of the glassware that make it shatter. For this reason, the graph in Figure 24 may look special as the experiments ended up being conducted at 250 °C (30 - 480 min.) and at 230 °C (1 – 30 min.). However, the evolution of the products is clear. Benzaldehyde builds up very quickly and is already found in considerable amounts within a minute. *trans*- and *cis*-Stilbene is formed meanwhile and is immediately followed by a steep increase in benzyl alcohol.

A tentative reaction sequence is shown in Figure 25. The reductions seem to be driven by

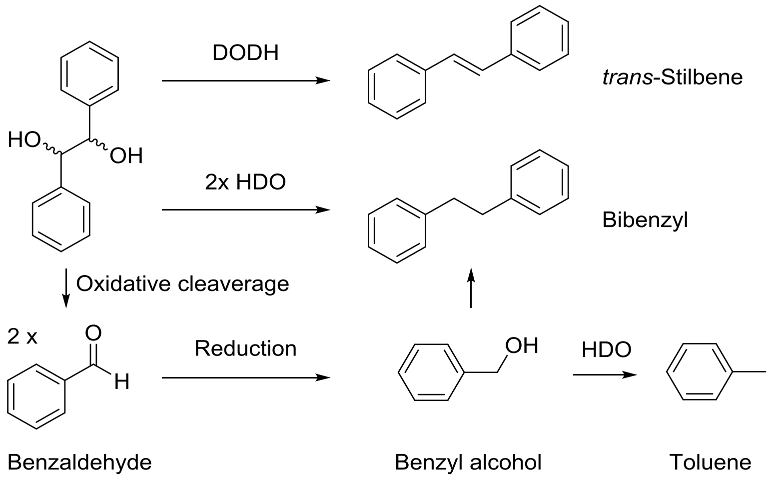


Figure 25. Reactions of hydrobenzoin catalyzed by NH_4VO_3 and driven by oxidative cleavage of the substrate.

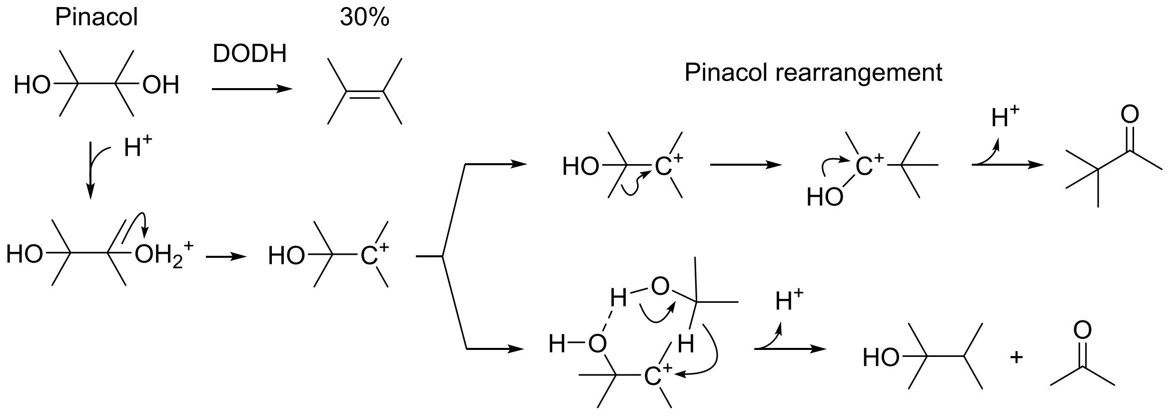


Figure 26. Treating pinacol with NH_4VO_3 in *i*PrOH, result in DODH and rearrangement reactions.

oxidative cleavage of hydrobenzoin to two equivalent of benzaldehyde. This give rise to high DODH activity in the very early stage. However, as the amount of hydrobenzoin is consumed, reduction of benzaldehyde to benzyl alcohol and subsequent HDO to toluene, outcompetes the deoxydehydration. The before mentioned publication about Mo-catalyzed HDO also observed that benzyl alcohol can be coupled to bibenzyl in the process.[40]

The supposedly less stabilized 1-phenyl-1,2-propanediol gave a majority of *trans*-β-methylstyrene (37%) as well, yet the only cleavage byproduct was toluene. In this case, the DODH seems to be at least partly driven by oxidation of *i*PrOH instead of oxidative cleavage of the substrate.

Deoxydehydration of pinacol was also attempted, as Nicholas and Chapman reported high yields of the corresponding alkene when $Bu_4N[VO_2(dipic)]$ was used as catalyst in correspondence with PPh_3.[66] The result reported here, show that 30% of the substrate undergoes DODH to yield 2,3-dimethyl-2-butene, along with a small amount of pinacolone (3%), that probably originate from a competing pinacol rearrangement. The sample also contained a small amount of 2,3-dimethyl-2-butanol (4%), which could be the result of a hydride transfer from *i*PrOH to the carbocation intermediate in the rearrangement (Figure 26). More interesting is the idea that the carbocation could add to the nearby OH group to form a temporary epoxide ring that is immediately deoxygenated to the alkene by the catalyst. Rhenium is known to catalyze the deoxygenation of epoxides with alcohol as solvent,[84] which make the idea more probable. However, the low yield of pinacolone and alkene, combined with the full conversion of the substrate renders this pathway less likely. Instead, the DODH of pinacol in *i*PrOH is thought to be driven mostly by oxidative cleavage to give two molecules of acetone, which would also explain the high conversion.

Rather than testing more model compounds, it was decided to look into DODH of glycerol. As a side product in the production of biodiesel, it is produced in huge amounts and is therefore a good

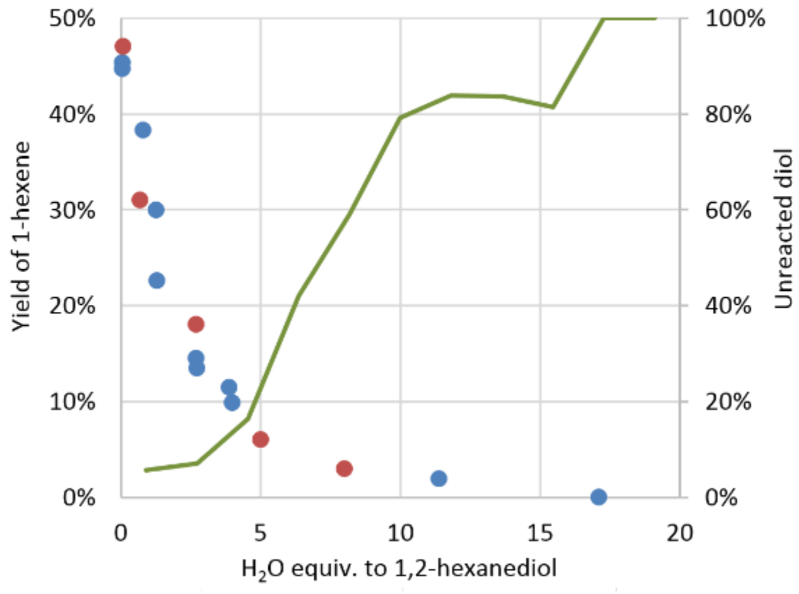
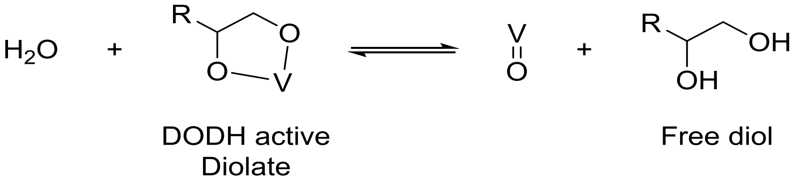


Figure 27**.** Addition of water to a DODH reaction of 1,2-hexandiol (reaction conditions B). *Blue dots*: NH_4VO_3 as catalyst. *Red dots*: $(NH_4)_6Mo_7O_{24}\cdot4H_2O$ (AHM) as catalyst.

candidate for real biomass compounds. The experiments were conducted under reaction conditions B, but without production of any allyl alcohol. However, the gas left in the headspace of the cylinder was directed through a solution of Br_2/CH_2Cl_2 to check if propylene is formed, but only very small amounts of the brominated alkene (1,2-dibromopropane) were detected with the GC. Reliable quantification of propylene was deemed impossible as the cylinders are expected to leak out nonpolar molecules that are this small. Similar experiments were done with 1,2-propanediol and ethylene glycol. Whereas ethylene glycol did not give any detectable ethylene, the gasses in the headspace after reaction of 1,2-propanediol contained significant amounts of 1-propene. The 3-isopropoxy-1,2-propanediol substrate, where one of the primary hydroxyl groups in glycerol is exchanged with an ether functionality, did undergo DODH to give 46% yield of 3-isopropoxy-1-propene at 86% conversion.

2.2.6 The DODH Reaction Inhibited by Water

Water is an inherent part of the products formed from DODH of any possible substrate. When the reductant is an alcohol, it is assumed that two molecules of H_2O will be formed for every turn in the catalytic cycle. For this reason, it is very interesting to obtain more information about the influence and role of H_2O during the reaction. Different amounts of water were added from the beginning, in a series of experiments carried out in the Swagelok cylinders (Figure 27). These results show a sharp decline in the DODH activity of NH_4VO_3, when exposed to increasing water concentrations. Addition of just a few equivalent of water to 1,2-hexanediol, is enough to drastically hamper the formation of the desired alkene. Even though, the water concentration is not expected to exceed more than twice that of the diol, this scenario apparently has the potential to lower the maximum yield of alkene from 50%, down to below 20%. The same tendency was found for the Mo compound, $(NH_4)_6Mo_7O_{24}\cdot4H_2O$ (AHM) that has otherwise proven to be an effective DODH catalyst.[68] An equilibrium state between the free diol substrate and the vanadium diolate, which is formed through condensation and release of H_2O, is a plausible explanation. Increasing amounts of water as the reaction progresses will force the equilibrium in Scheme 21 towards the right hand side and thereby stop the reaction.



Scheme 21. A possible equilibrium state between the free diol and the DODH active diolate.

The question is however, if water only has a negative effect on the DODH. Calculations on Re and Mo, show reaction pathways in which either water, or an alcohol, is involved as co-ligands.[63,73] Therefore, it cannot be ruled out that a small amount of water is actually necessary for the catalytic cycle to be active, but it seems unlikely as the experiments are performed with an alcohol as the solvent.

Methods to Remove Water

How removal of the water will influence the DODH reaction is unknown. In a standard experiment, full conversion and 50% alkene yield is obtained after 18 hours. Effective removal of the water, that is produced during the DODH reaction, could allow for a shorter reaction time. The following experiments, in which water removal have been attempted, were therefore shortened down to 480 min. (8 h), which would, in a standard experiment on 1,2-decanediol, within the same timeframe, result in 34% 1-decene at 89% conversion.

Figure 28. Metal container used to protect the molecular sieves from the magnetic stir bar.

Different ideas to remove water from the reaction mixture were tested. A very common way to remove water in organic synthesis is to use molecular sieves. A small metal container that fitted into the PTFE cup, of the autoclave, was prepared as a means to avoid physical destruction of the beads by the magnetic stir bar (Figure 28). This was necessary because the resulting mixture was otherwise impossible to filter. An experiment employing 4Å molecular sieves in a DODH mixture with 1,2-decandiol and heated for 480 min, gave a yield of 18% 1-decene at 51% conversion. The result is therefore not as good as when sieves are not used (34% 1-decene, 89% conversion).

A control experiment in the autoclave, was done to elucidate upon the efficiency at which molecular sieves works when heated to 230 °C in isopropanol. The PTFE cup was charged with 150 ml *i*PrOH and an IR background spectrum recorded by submerging the IR probe into the liquid (see experimental section). Thereafter, 2 wt% H_2O was added and a spectrum of the bending mode in water (~1645 cm^{-1}) was recorded (Figure 29, *turquoise line*). Activated molecular sieves (30 g, 3Å, beads) were used to dry the sample and another spectrum recorded (*green line*). Nitrogen pressure was applied and a sample extracted from the autoclave after 480 min at 230 °C. The sample was quickly filtered and a fourth spectrum obtained (*purple line*). Integration of the peak areas was not done, but just by comparison of the areas in Figure 29 it is evident that the molecular sieves are not binding the water strongly enough.

Carbon molecular sieves are much more persistent to heat and pressure, and was thus considered a possible substitute. A batch of Carboxen 569 (20-45 mesh) was therefore bought from Sigma Aldrich. These are small spherical pellets of a porous carbon material with pore diameters between 5 - 8 Å and they should therefore allow molecules with sizes relative to C_2-C_5 *n*-alkanes to enter their cavities. In a reaction mixture that consist of C_{10}-molecules, hexadecane, 2-octanol and H_2O,

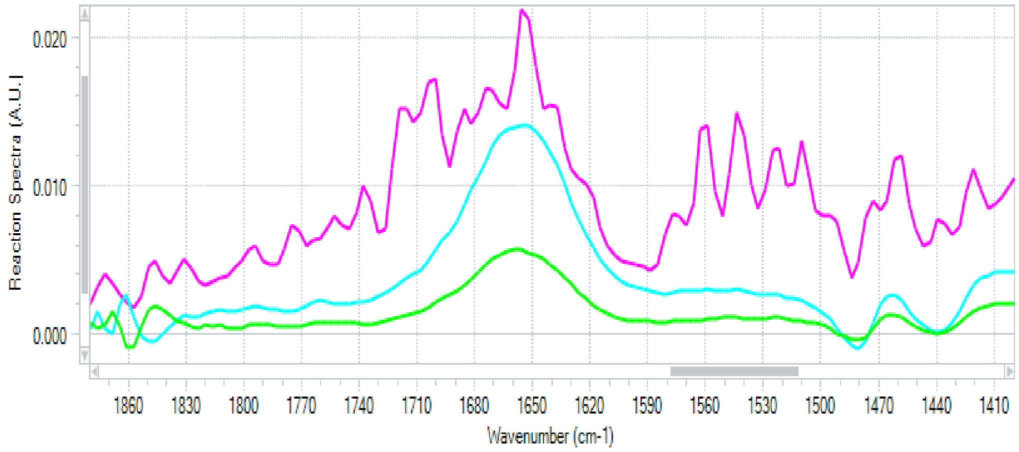
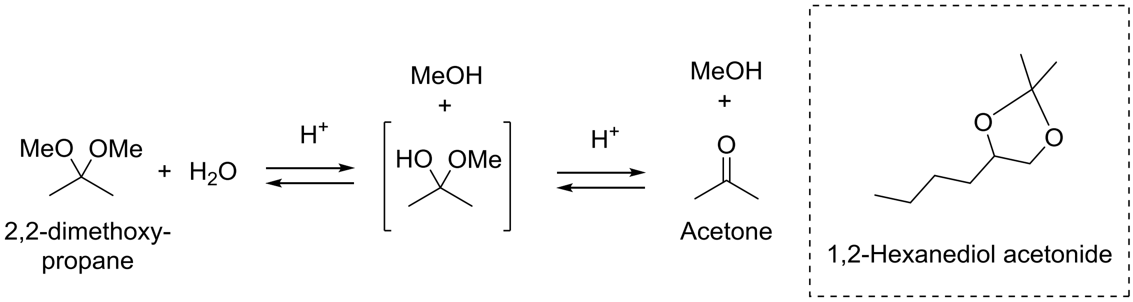


Figure 29. IR experiment showing the bending mode in water at 1645 cm^{-1}. *Turquoise line*: *i*PrOH with 2 wt% H_2O. *Green line*: after water removal with sieves. *Purple line*: after heating of the dried *i*PrOH to 230 °C, followed by filtration of the sample.

only water is small enough to enter the inner parts of the Carboxen pellets. If the sieves constitute a large enough volume of the total reaction mixture, then it may dry out the residing sample, simply because of the larger volume that only H_2O can enter. In this way, the ability of the Carboxen sieves to remove water would be different from the traditional silica based sieves, because binding of the H_2O to the material is not necessary. So even though the pellets are reported to be hydrophobic, the idea was still thought to be valid, as it does not rely on chemical binding and, because the pore sizes in the pellets are much bigger than the diameter of a water molecule. One experiment was performed with 1,2-decanediol in 2-octanol and for 480 min. under reaction conditions A. The yield of 1-decene was 34%, and it is thus slightly better than what is obtained in an experiment with 2-octanol as the solvent and without any sieves (31% 1-decene). Both of the samples showed a complete removal of the substrate, with no new compounds appearing in the GC or GCMS.

Another possible way of removing water from the hot autoclave, is to add a chemical to the reaction mixture that removes it in the process. The difficulty with this approach is to avoid reaction of the added chemical with the substrate or solvent. One idea was to use a ketal as the water scavenger, as they are formed through nucleophilic addition of an alcohol to a ketone with subsequent release of H_2O. The reverse reaction should therefore remove a molecule of water from the reaction mixture (Scheme 22).

As DODH using an alcohol as reductant, is expected to yield two molecules of water for every diol converted, it was first deemed necessary to add at least two equivalent of 2,2-dimethoxypropane. The experiment was conducted twice on 1,2-hexanediol under reaction



Scheme 22**.** The equilibrium states between 2,2-dimethoxypropane and acetone, separated by formation of a hemiketal. A molecule of water is removed in this process. Reaction of 1,2-hexanediol with acetone or 2,2-dimethoxypropane could trap the diol as 1,2-hexanediol acetonide.

conditions B (1020 min) and both experiments gave 27% of 1-hexene. Instead of the diol showing up in the GCMS after the reaction, a significant peak, which could be related to the ketal formed by reaction of 1,2-hexanediol with acetone, was observed (Scheme 22). A possible solution to avoid that all of the substrate gets trapped in the ketal form, is to add less 2,2-dimethoxypropane than diol. Then the reaction mixture should always contain some free substrate, that is ready to undergo DODH to form the alkene and two molecules of H_2O. The formed water could then react with 1,2-hexanediol acetonide to release some more of the trapped diol. Only a very small improvement over the previous experiment could be achieved when 0.75 equivalent of 2,2-dimethoxypropane was used (39% 1-hexene, 92% conversion). It was therefore concluded that this way of removing water is unlikely to be suitable under the necessary conditions.

Another similar attempt was based on the reaction between trimethyl orthoformate and water. The only drawback with this plan, is that at this temperature the orthoformate may as well attack the diol and form a dioxolane compound, that may decompose to the corresponding alkene (Scheme 8). An experiment employing 3 equivalent of triethyl orthoformate to 1,2-decanediol, gave 45% of 1-decene after 480 min. (8 h.), under reaction conditions A. All of the substrate had reacted and a new peak in the GCMS spectrum was thought to be the expected dioxolane compound. The experiment was therefore repeated with a longer reaction time, but roughly the same result (48% 1-decene) was achieved after 4320 min (72 h.).

Inorganic CaO, Mg and Fe are known to react with water[89,90] and they were therefore tested in a few experiments. The dehydration of alcohols with CaO is an old method to dry alcohols and it was therefore expected not to trap or otherwise interfere with the solvent or the diol. However, when 6 g of CaO (100 mmol) was added to a reaction of 1,2-decanediol (reaction conditions A, 480 min), a lot of precipitate was obtained that was nearly impossible to filter. The GC and GCMS spectra of

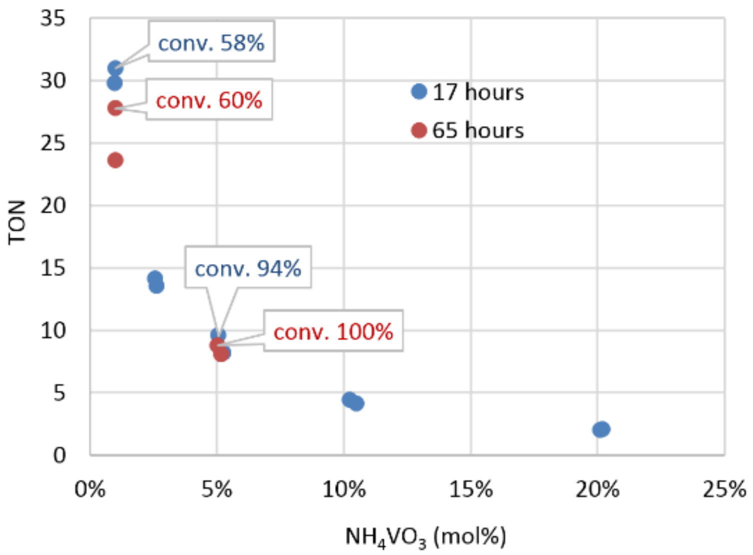


Figure 30. Turn-over numbers (TON) for different loadings of NH_4VO_3. Reaction conditions B.

the filtrate only showed a tiny amount of 1-decene along with the reference. The oxide had clearly trapped the diol and when the precipitate was treated with dilute HCl, a range of different GC peaks appeared with retention times close to that of the diol. Addition of 2 equivalent Mg(0) turnings, or 2.5 equivalent of Fe(0) powder, only resulted in lower yield of alkene than would usually be obtained.

2.2.7 Recyclability of the Catalyst

How well a catalyst performs is not evident solely from the yield of alkene in a test experiment. Instead, it is better to look at turn-over numbers (TON) as it accounts for both efficiency and durability of the catalyst. The TON is simply the amount of substrate molecules that each vanadium center can convert into the corresponding alkene, before it becomes deactivated by precipitation or transformation into unreactive V compounds. The TON is thus very dependent on the reaction conditions in which the catalyst operates. A number of batch experiments were used to investigate the turn-over number of NH_4VO_3 at different catalyst loadings (Figure 30). With a reaction time of 1020 min (17 h.) and 5 mol% ammonium metavanadate, which is the catalyst loading that give the highest yield of alkene, the TON was calculated to be 9 based on the yield of alkene (48% 1-hexene, 94% conversion of diol). A similar, but much longer experiment, gave full conversion of the substrate after 3900 min. (65 h.) and the same turn-over number. A more correct value was obtained when 1 mol% catalyst was added, as full conversion was not reached. In this this case,

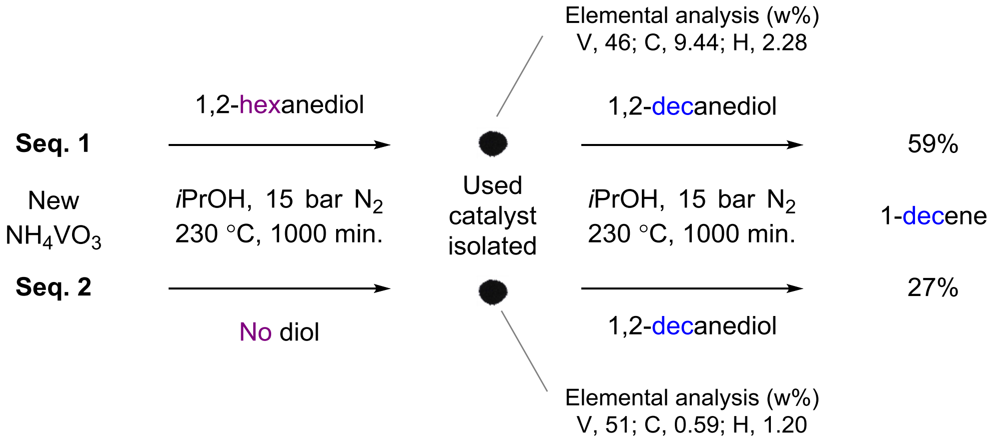


Figure 31. Two different reaction sequences, to investigate the reusability of the catalyst. The used catalyst that was produced with 1,2-hexandiol (120 mmol), gave much higher alkene yields in the second DODH step. Reaction conditions A.

31% of the initial substrate had been turned into 1-hexene after 17 hours, and with incomplete conversion of the diol. Almost the same result was obtained after 65 hours, which means that the catalyst must have died completely already within the 17 hour timespan. The maximum TON that can be achieved with NH_4VO_3 under the reaction conditions, was thus calculated to be 30. Another take-home message, is that the amount of product and thereby the TON stays the same for both timespans which means that 1-hexene does not escape the cylinders in any considerable amount.

Studies especially aimed at determining the maximum TON in DODH reactions are generally very scarce, which is probably because most of the catalytic systems exhibit low stability and efficiency. The available numbers are therefore not precise, yet most of the Re-catalyzed DODH systems reported in the literature, are thought to have turn-over numbers below 200.[68] Raju *et al.*[57,91] however, reported a new Re catalyst in 2013 and realized that their system was likely to have better DODH properties in terms of turn-over number, than any other published Re system. For this reason, they chose to conduct an experiment on their 1,2,4-tri(tert-butyl)cyclopentadienyl trioxo-rhenium catalyst ($Cp^{ttt}ReO_3$) with the specific aim of determining the maximum obtainable turn-over number. A TON of 1400 per Re atom was achieved, which is believed to be the best result obtained for any DODH reaction so far. Their system, was built on the strong PPh_3 reductant and conducted in chlorobenzene, thus it cannot be directly compared to the V-system reported here.

For some reason, the vanadium catalyst is not very good when used in a single batch experiment. To gain more knowledge about the factors that determine how long the active species survives, it was decided to reuse the catalyst from a subsequent experiment in which an aliphatic-1,2-diol with a different carbon chain length was used (Figure 31). Correct yields would therefore be obtained

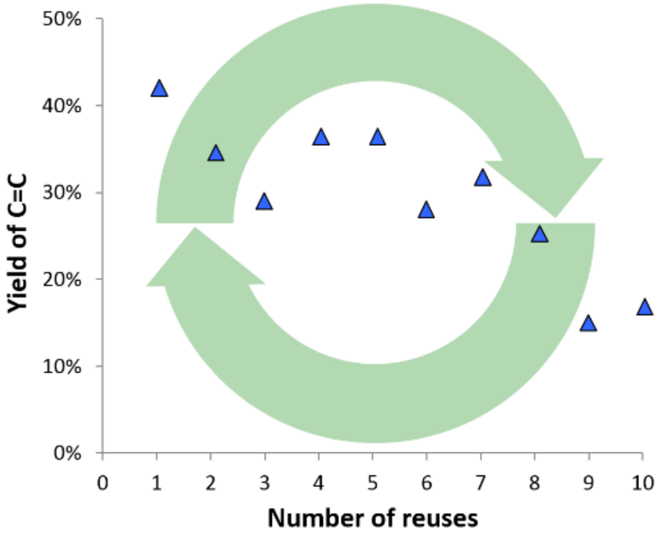


Figure 32. Recycled vanadium catalyst, with 1,2-decanediol as the substrate. Reaction conditions A (new substrate and solvent added before every reuse. Internal reference added after each experiment).

even if the catalyst to be recycled, should contain diol from the proceeding experiment. Two sequences were conducted under reaction conditions A; one in which the catalyst to be recycled is produced with 1,2-hexanediol (5 mol% NH_4VO_3 to diol) (Seq. 1), and another without any diol present (Seq. 2). Elemental analysis on the isolated black powders, showed that carbon constitute 9.4 wt% of the catalyst produced with 1,2-hexanediol, whereas the other powder, contain only vanadium and oxygen. In the following DODH of 1,2-decanediol, a much better yield of alkene was achieved in Seq. 1 (59% 1-decene), than in Seq. 2 (27% 1-decene). The two sequences therefore illustrate how important it is for vanadium to be constantly in contact with some diol, to prevent deactivation of the catalyst.

A longer sequence of experiments was performed to find the maximum number of times that the catalyst could be recycled. After each individual run, the catalyst was filtered from the rest of the sample and washed with *i*PrOH. The internal reference was added to the filtrate and the sample analyzed as usual. Fresh 1,2-decanediol (40 mmol), *i*PrOH, and the recycled catalyst was put into the PTFE cup and treated for 1020 min, as described for reaction conditions A. The results are summarized in Figure 32, in which it is evident that the catalyst is somehow regaining some activity when first separated and then reused in a new batch reaction. The vanadium catalyst was reused 10 times, at which point it was still somewhat active. This behavior of the catalyst may be connected with the previously described inhibition caused by water. Maybe the water free environment in the

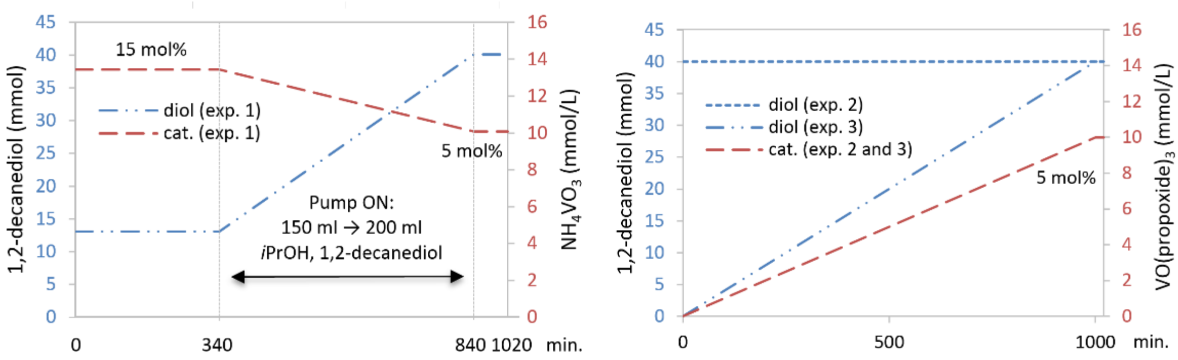


Figure 33. Pump experiments 1, 2 and 3, in which *i*PrOH and 1,2-decanediol is pumped into the autoclave over a period of 17 hours (1020 min).

Table 14. Results When Substrate and Catalyst is Added Over Time.[a]

Exp.	Pumped in	Conv. [%]	Yields [%] of C=C	C=O	1°OH
1	1,2-decanediol + *i*PrOH	59	27	4	7
2	VO(propoxide)$_3$ + *i*PrOH	100	53	3	7
3	1,2-decanediol + VO(propoxide)$_3$ + *i*PrOH	57	34	3	8

[a] The autoclave was connected to a HPLC pump. See experimental section for more detail.

beginning of each run help to regenerate the catalyst, while the decline in alkene yield is caused by loss of the catalyst when the samples were filtered.

Lots of speculation and ideas on how to deal with the water and catalyst lifetime were considered, but in the end it was decided to go back to simple experiments in which the individual components of the reaction mixture were added over time. To do so, an HPLC pump was connected to the autoclave through the thermometer fitting, and then different solutions were slowly pumped in (see experimental section for more detail). The results are summarized in Table 14 and the experiments illustrated in Figure 33. In exp.1, the substrate was dissolved in *i*PrOH and added during a period of 500 minutes (27 mmol). The reaction mixture also contained some 1,2-decanediol (13 mmol) to begin with, so that the catalyst would not get deactivated. A low amount of 1-decene was achieved and still with an alkene to conversion ratio of 0.5.

In experiment 2 the catalyst VO(propoxide)$_3$, which is a liquid, was diluted with *i*PrOH and added slowly to a batch containing 40 mmol of 1,2-decanediol from the beginning. As the catalyst is more effective at lower concentrations (higher turn-over number) and seems to die quickly in the batch experiment, the effect of adding the catalyst during the reaction was investigated. Indeed, the 53% yield of 1-decene that was obtained is rather good because most of the time the amount of vanadium is way below 5 mol%, while the mixture is diluted to half of that in a normal experiment.

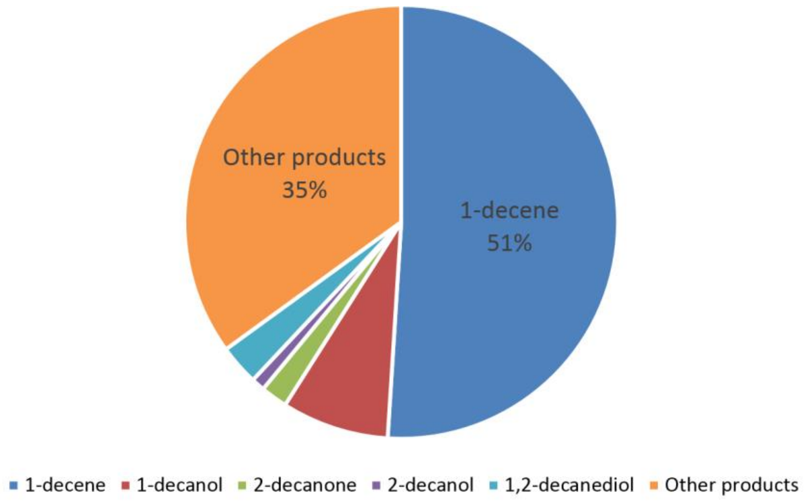


Figure 34. Typical distribution of products in an experiment with NH_4VO_3.

However, the conversion was again complete and higher alkene yields unlikely to be within reach by this method. In the last of the pump experiments, both the substrate and the catalyst were added simultaneously to the autoclave. This resulted in 34% yield of 1-decene, which is better than the result obtained in the first experiment. Again, the dilute catalyst seems to have an increased performance until it stops working.

2.2.8 Intermediates and Other Products

All of the experiments so far have shown a 2:1 relationship between conversion and yield of alkene. The distribution of products after a typical experiment with NH_4VO_3 is depicted in Figure 34. It clearly shows that roughly 35% of the added substrate end up as unidentified compounds. None of the traditional methods (GC, GCMS, LCMS, NMR) were able to detect any compound in large enough amounts to explain the missing substrate. The following sections discuss some experiments that were meant to give a better understanding of the side products.

DODH on 1,2-Tetradecanediol in Dodecane.

Molybdenum catalyzed deoxydehydration has been reported to convert 1,2-tetradecanediol into 1-tetradecene in 43% yield, when conducted in dodecane within an open glass vial at 200 °C.[67] The Mo-catalyst was found to be reduced through oxidative cleavage and deformylation of the substrate. Even though there have been no signs of products formed from cleavage in the vanadium catalyzed

DODH of terminal aliphatic-1,2-diols, two experiments similar to those reported for Mo were conducted. The first experiment was stopped after 60 min. (as for Mo), but only 4% of 1-tetradecene could be detected in the mixture, in which everything was not in solution. Another longer experiment gave the same low yield of alkene after 360 min, even though there was no precipitate in the resulting solution. The results seem to exclude the possibility that vanadium DODH should be strongly affected by oxidative cleavage of the substrate.

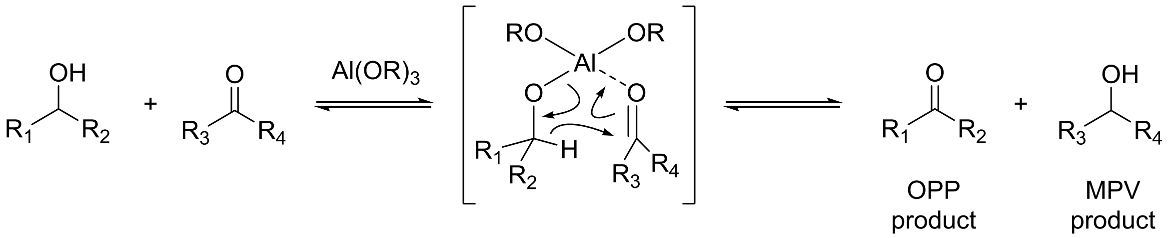
The MPV Reduction and Tishchenko Disproportionation

To get a better insight into the chemistry of aldehydes and ketones under the reaction conditions, these types of compounds were tested with and without 1,2-hexanediol in the reaction mixture. When hexanal is treated with NH_4VO_3 in *i*PrOH under reaction conditions B, then 87% 1-hexanol is obtained without anything else in the GC spectrum (Table 15, Exp. 1). In this case the reductant is expected to be isopropanol. Also, if decanal (20 mmol) and 1,2-hexanediol (10 mmol) are subjected to the same conditions, then DODH of the diol is observed along with reduction of the aldehyde (Table 15, Exp. 2). The alkene yield is only a bit lower than performed without the aldehyde, so it seems safe to conclude that acetal formation cannot explain the missing products.

Even though 2-decanone is a minor product in Figure 34 the formation and further reactions of the ketone is likely to be interesting. When 2-hexanone is treated, without any diol in the mixture, only 13% is converted to 2-hexanol. However, when 1,2-hexanediol (10 mmol) is added to the reaction of 2-decanone (20 mmol), then 45% of the ketone is reduced to the corresponding alcohol (Table 15, Exp. 4). The DODH process is almost unaffected, thus oxidation of the diol alone cannot explain all the reduced products that are obtained. Therefore, isopropanol has to be oxidized to acetone in this experiment. A possible explanation is that a V(diolate) complex is allowed to form when 1,2-hexanediol is present in the reaction mixture, and that it catalyzes the Meerwein-Ponndorf-Verley (MPV) reduction[92] of ketones to alcohols (Scheme 23).

Table 15. Aldehydes and Ketones Under Reaction Conditions B.

	Substrates		Products			
Exp.	Carbonyl	DODH	Conv.	Carbonyl	Conv.	DODH
1	Hexanal		100%	87% 1-hexanol		
2	Decanal	1,2-hexanediol	100%	76% 1-decanol	88%	43% 1-hexene
3	2-Hexanone		13%	12% 2-hexanol		
4	2-Decanone	1,2-hexanediol	45%	45% 2-decanol	91%	40% 1-hexene

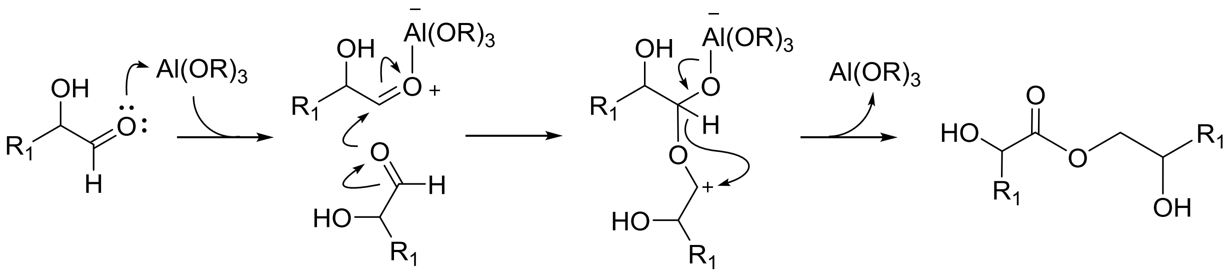


Scheme 23. The MPV reduction (OPP oxidation) of 2-hexanone to 2-hexanol catalyzed by an aluminum alkoxide.

The MPV reduction is usually catalyzed by aluminum triiosopropoxide, but other metal alkoxides have also been found able to catalyze the reaction.[93,94,95] It is therefore possible that vanadium can do the same, and efficiently enough to account for the observed conversion of 2-hexanone to 2-hexanol, by oxidation of isopropanol to actone.

The 1,2-hexanediol in a standard DODH experiment, could be oxidized to 1-hydroxy-2-hexanone or 2-hydroxyhexanal by MPV reduction (Oppenauer oxidation, OPP) of the acetone that is produced when isopropanol is used as the reductant (Figure 35). If this is a major cause to the missing substrate, then the 2-hydroxyl species have to undergo further reactions into a range of different compounds, or compounds that cannot be detected easily. The 2-hydroxyhexanal could take part in the Tishchenko disproportionation depicted in Scheme 24, in which two molecules of an aldehyde is coupled to give a corresponding ester. This reaction is also catalyzed by an aluminum alkoxide, so if vanadium facilitates the MPV reduction it seems more reasonable to assume that it will also catalyze the disproportionation.

Another possibility is that the aldehyde undergo further oxidation to 2-hydroxyhexanoic acid, that react with the solvent to form isopropyl 2-hydroxyhexanoate. This ester is always found in the resulting reaction mixture, but was for a long time mistaken to be 1-isopropoxy-2-hexanol, which is obtained in Mo-catalyzed DODH.[68] Reaction of DL-2-hydroxyhexanoic acid in isopropanol, gave a solution containing the acid and isopropyl (*R*,*S*)-2-hydroxyhexanoate. Although the retention time



Scheme 24. The Tishchenko disproportionation of two aldehyde molecules to form an ester.

and GCMS spectrum of the peak obtained after DODH of 1,2-hexanediol, fitted with the prepared ester, it was further verified to be isopropyl (*R*,*S*)-2-hydroxyhexanoate by changing to a chiral GC column and observing that the peak splits up into two distinct peaks (Figure 36). Preparation of a clean sample of the ester failed, and it was therefore not possible to make a trustworthy GC response factor for the compound. However, when using the factor for isopropyl (*R*)-lactate and increasing that value by a reasonable amount due to the longer carbon chain in isopropyl (*R*,*S*)-2-hydroxyhexanoate, it was found that the ester is likely to constitute roughly 10% of the initial substrate. The amount of missing products in a typical DODH experiment on terminal aliphatic-1,2-diols, is thereby lowered to 25%.

Both of the esters, the 2-hydroxyhexanal, and the 1-hydroxy-2-hexanone may be prone to form polymerization products that are difficult to distinguish from the rest of the reaction mixture using NMR, LCMS or GCMS. In a typical experiment employing 20 mmol of 1,2-hexanediol, 5 mmol of the initial substrate will be missing. If it is forming a polymer with many repeating units, the concentration of the polymer can become very low, which will make it difficult or even impossible to detect and measure.

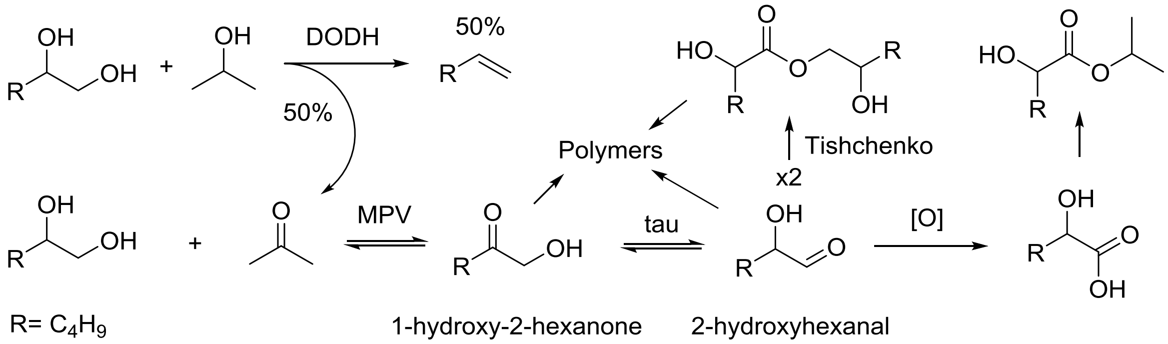


Figure 35. Overview of the different reactions that could be responsible for the missing substrate.

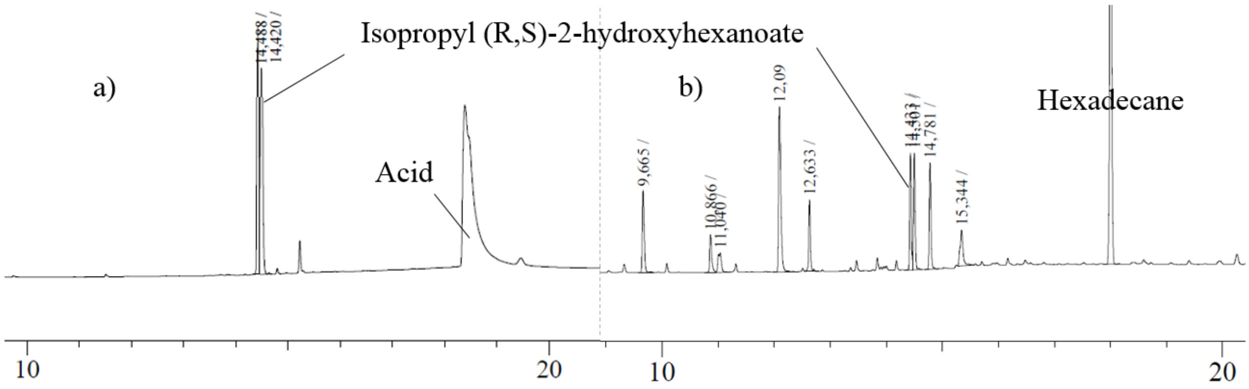


Figure 36. GC spectra when using the chiral column a) Reaction mixture of DL-2-hydroxyhexanoic acid in isopropanol. b) Spectrum of mixture obtained after DODH of 1,2-hexanediol.

2.3 Conclusion

Autoclave experiments of the vanadium catalyzed deoxydehydration of vicinal diols, using an alcohol as a combined solvent and reductant, have been investigated. A range of alcohols were tested as reductants and the secondary alcohol, isopropanol, found to give the best results. Different vanadium compounds were also examined for their catalytic activity, but only minor changes in the conversion, product distribution and alkene yields were observed. A prototype reaction consisting of 1 mol% NH_4VO_3 in *i*PrOH, was able to convert vicinal diols with one primary and one secondary OH group (e.g. 1,2-hexanediol) into the corresponding alkene in about 50% yield. These results may be achieved when the mixture is heated to 230 °C for 17 hours. The above protocol was used to make comparable results between the various experiments. When the unreactive 2,3-dihydroxynaphthalene was added, an increase in the primary alcohol (1-hexanol) was found. Speculation about other similar results lead to the proposal that the active V-species in the DODH is mononuclear, whereas the primary alcohol may be formed from a binuclear compound.

The V-catalyzed DODH displays a strong selectivity for the diols that contain exactly one primary and one secondary hydroxyl group. When either the *cis* or *trans* stereoisomers of 1,2-cyclohexanediol was used as the substrate, only very small amounts of cyclohexene could be detected afterwards. Also, a significantly lower yield of 1-hexene was found upon addition of *cis*-1,2-cyclohexanediol to a prototype reaction of 1,2-hexanediol (19% alkene), whereas addition of the *trans* version had a much smaller influence (43%). This observation may be explained by the *trans* isomer having problems coordinating to the vanadium center with both hydroxyl groups.

The straight chain 3,4-hexanediol, *cis*-1,2-cyclooctanediol, 1,4-anhydroerythritol and 1,4-anhydrothreitol were all found to be largely unreactive, which underlines the aforementioned selectivity. The more reactive diols with only secondary alcohol groups, such as hydrobenzoin and pinacol, allowed for oxidative cleavage to drive the reaction instead of oxidation of isopropanol.

Water is an important product in DODH, because it has been found to strongly inhibit the reaction. Various methods to remove it, *in-situ*, have been tried, but without much success. However, removal or even control of the concentration of water could be the way forward to obtain better yields and turn-over numbers. Though the TON in a batch experiment is low, the catalyst may be used several times if the reaction mixture is replaced with new solvent and substrate.

The reported results have clarified that the V-catalyzed DODH reaction is different from the reaction catalyzed by Re or Mo. The inability of vanadium to undergo oxidative cleavage of most of the substrate molecules, is an advantage that may open up for better yields and a broader scope of applicable reductants. The selectivity towards substrates with exactly one primary and one secondary hydroxyl group, is also a special feature that is not observed when using Mo or Re catalysts, even though they share a common requirement for the hydroxyl groups to be able to adopt a *cis* stereo configuration. It is possible that the newly postulated radical mechanism in V-catalyzed DODH is somehow connected to the observed preference for vicinal, terminal, diols, even though such a connection has not been found yet. The selectivity might allow for development of a catalyst that is able introduce double bonds into specific sites in molecules containing other OH groups. Development of such a catalyst is likely to be worth the effort because the ability to produce specific target molecules is desired in industry.

Compared to the other experimental results on V-catalyzed DODH, the reported yields of alkene herein, are not as good. However, the idea of using an alcohol for solvation and reduction, deserved a thorough investigation solely because of the potential renewability, of the alcohol, by hydrogenation of the produced ketone. The much stronger oxidant, PPh_3, is suitable for scientific purposes, but likely to be too expensive for large scale production. Carbon monoxide gas however, is an interesting candidate for reduction, even though it is toxic and gasses usually are more difficult to handle than liquids.

The many impressive results on Re-catalyzed DODH, especially those employing an alcohol, are promising signs that such high yields could also become true for Mo and V, if the right catalyst systems are discovered. However, the price difference between Re and V is so large that the 50 % alkene yield, that has been found in this work, should be regarded as a good result, even though there is room for improvement. When compared to Mo, vanadium may have an advantage by being less prone to facilitate oxidative cleavage of the substrate, thus allowing better yields.

Further investigations on the subject, should probably aim at synthesizing different vanadium complexes and test those at lower temperatures than 230 °C. A lower reaction temperature could allow for *in-situ* separation of the produced water, less production of unwanted side products and better stability of the catalyst. The alternative to this plan, is to use more time on discovering the precise whereabouts of the substrate that goes missing, and find a way to suppress this unwanted process. However, after having worked with V-catalyzed DODH in *i*PrOH for a while, the first plan seems bolder, more interesting, and may even have a better chance for success.

2.4 Experimental Section

Instrumentation

The quantitative analysis of products and conversion of substrate was determined with a Shimadzu GC-2010 gas chromatograph equipped with an Equity-1 column (30 m, 0.25 mm inner diameter, 0.25 µm film thickness). Hexadecane was used as internal reference for determination of product yields. Characterization of products was done by a Shimadzu GCMS-QP2010S system equipped with an Equity-5 column and electron ionization.

NMR spectra were acquired on a Bruker (Karlsruhe, Germany) Avance III NMR instrument equipped with a 9.4 Tesla magnet (400 MHz ^{1}H frequency) and a BBO CryoProbe Prodigy at 290 K. One-dimensional ^{1}H and ^{13}C spectra were acquired by sampling 32768 complex data points for both nuclei during acquisition times of 4.0 and 1.3 seconds for ^{1}H and ^{13}C, respectively.

The IR measurements where done with a Mettler-Toledo ReactIR iC10 Fourier-transformed IR spectrophotometer with a K6 mirror conduit that gives a N_2 purged pathway for the IR beam to travel from the attenuated total reflection based probe which is fitted with a silicon crystal (SiComp) at the probe tip and back to the HgCdTe detector. The probe was placed vertically into the reaction mixture. The microwave experiments were conducted on a Biotage Initiator+.

Reaction Conditions A

40 mmol substrate, 5 mol% catalyst (with respect to vanadium, NH_4VO_3 if not otherwise stated), 500 mg hexadecane (internal standard), and 100 ml of solvent (*i*PrOH if not stated otherwise), was put into a 300 ml PTFE cup. The teflon cup was placed in a 400 ml Berghof autoclave with a magnetic stir bar. The autoclave was placed in the heating mantle, closed properly, and then 15 bar of N_2 gas was added. The computer controlled heating plate was set to 230 °C with the stir bar at 500 r.p.m. Most of the experiments reached pressures around 50-70 bar (Figure 37). The temperature was usually stable just a few degrees below the chosen temperature. When the autoclave had cooled down, the pressure was slowly released and the mixture filtered with suction. The amount of products and residual substrate was determined by GC, while the characterization of the compounds was resolved by GCMS analysis. The GC areas for the diols are generally less reliable than for the other analyzed compounds, and the listed conversions may therefore deviate by approximately ±10 - 20%.

The yields were calculated using response factors (RF), that connects the obtained GC area for a known amount of a reference compound (A_{ref}), with the area, that is obtained for the product (A_x). The response factor for a product is expressed as in eq. 3, where M_{ref} and M_x are the concentrations of the reference and the product, respectively.

$$\mathrm{RF_x} = \frac{\mathrm{A_x} \cdot M_{\mathrm{ref}}}{M_{\mathrm{x}} \cdot \mathrm{A_{ref}}} \qquad \text{eq. 3}$$

Because it is all diluted in the same amount of solvent, the volume parts of the concentrations cancel out. The formula will then become as in eq. 4.

$$\mathrm{RF_x} = \frac{\mathrm{A_x} \cdot n_{\mathrm{ref}}}{n_{\mathrm{x}} \cdot \mathrm{A_{ref}}} \qquad \text{eq. 4}$$

An expression for the amount of product is given in eq. 5. Here, $\mathrm{M_{ref}}$ is the molar mass and $\mathrm{g_{ref}}$ the number of gram of reference that was added to the solution.

$$n_{\mathrm{x}} = \mathrm{RF_x^{-1}} \cdot \frac{\mathrm{g_{ref}} \cdot \mathrm{A_x}}{\mathrm{M_{ref}} \cdot \mathrm{A_{ref}}} \qquad \text{eq. 5}$$

The percentage of substrate that has been converted to the product, is then given by eq. 6. The terms $\mathrm{M_{sub}}$ and $\mathrm{g_{sub}}$ are the molar mass and amount of the substrate molecule, respectively.

$$\mathrm{mol_x\%} = \frac{\mathrm{A_p} \cdot \mathrm{g_{ref}} \cdot \mathrm{M_{ref}^{-1}} \cdot \mathrm{M_{sub}}}{\mathrm{RF_p} \cdot \mathrm{A_{ref}} \cdot \mathrm{g_{sub}}} \cdot 100 \qquad \text{eq. 6}$$

The conversion is calculated accordingly to eq.7. Here, $\mathrm{A_{sub}}$ is the GC area, $\mathrm{RF_{sub}}$ is the response factor, and $\mathrm{g_{sub}}$ the amount of substrate added from the beginning.

$$\mathrm{conv.\%} = 1 - \frac{\mathrm{A_{sub}} \cdot \mathrm{g_{ref}} \cdot \mathrm{M_{ref}^{-1}} \cdot \mathrm{M_{sub}}}{\mathrm{RF_{sub}} \cdot \mathrm{A_{ref}} \cdot \mathrm{g_{sub}}} \cdot 100 \qquad \text{eq. 7}$$

Reaction Conditions B

These experiments are the same as under reaction conditions A, except that they were conducted on half scale within a 150 ml Swagelok cylinder. An aluminum block was placed on top of a heating plate and the temperature controlled by a thermo-control, which was situated in the top part of the aluminum-block. The temperature was set to go up to 250 °C and the cylinders put into the aluminum-block once 235-240 °C had been reached. Unless otherwise noted, the experiments were stopped after 1020 min. It was not possible to measure the pressure or temperature evolution within the cylinders, but a thermo-control with logging function, was used to log the temperature between the side of a cylinder and the block (Figure 37).

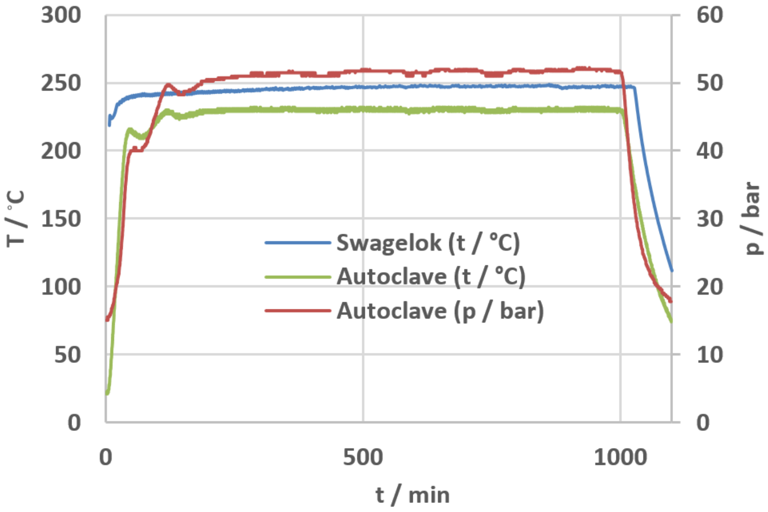


Figure 37**.** Temperature profiles for experiments in the autoclave and the Swagelok cylinders. The pressure profile for the autoclave experiment is also depicted, but could not be monitored in the cylinders.

Microwave Experiments

<u>Experiments at 230 °C (1 - 20 min.) and 250 °C (20 – 480 min.) were prepared as follows:</u>

A solution of 2.1758 g hydrobenzoin (mixture of stereoisomers), 496.2 mg hexadecane in 80 ml 3-pentanol was prepared. Then 4 ml of the solution was added to a 2 - 5 ml microwave vial that had already been charged with 3.3 mg NH_4VO_3. This give a samples consisting of 0.5 mmol hydrobenzoin, 24.8 mg hexadecane and 5.5 mol% catalyst. The samples were premixed for 10 s, before heating began. After the experiments were finished, the samples were analyzed on GC and GC/MS as usual.

Pump Experiments

The starting solutions for each experiment was mixed in the cavity of the autoclave (no Teflon cup) with a magnetic stir bar. A ring of Teflon was put in between the top- and bottom part of the autoclave and then it was sealed tight. The pump was connected through the inlet, originally suited for the inside electronical thermometer. For this reason, the temperature was measured in between the heating mantel and the autoclave. We had beforehand, found that when setting the inside temperature control to 230 °C (as under reaction conditions A), then the outside temperature was 200 °C. The pump experiments were thus conducted at roughly 230 °C, by controlling the temperature on the outside.

Exp. 1

Starting solution: 150 ml *i*PrOH, 235.7 mg NH_4VO_3, 506.3 mg hexadecane, 15 bar N_2, 2.2781 g 1,2-decanediol (13 mmol). *Pumped solution*: 0.54M 1,2-decanediol in *i*PrOH (0.1 ml/min. in 500 min.).

Exp. 2

Starting solution: 100 ml *i*PrOH, 508.1 mg hexadecane, 15 bar N_2, 6.9726 g 1,2-decanediol (40 mmol). *Pumped solution*: 0.02M $VO(propoxide)_3$ in *i*PrOH (0.1 ml/min. in 1000 min.).

Exp. 3

Starting solution: 100 ml *i*PrOH, 508.0 mg hexadecane, 15 bar N_2. *Pumped solution*: 0.4M 1,2-decanediol and 0.02M $VO(propoxide)_3$ in *i*PrOH. (0.1 ml/min. in 1000 min.).

Deoxydehydration of 1,2-Tetradecanediol in Dodecane

An open test tube was charged with 1 mmol 1,2-tetradecanediol, 50 mg hexadecane, 2 ml dodecane and 5 mol% NH_4VO_3. The tube was placed in a pre-heated aluminum block with stirring and the temperature set to 200 °C. The thermometer was placed in another tube that contained the same amount of dodecane. The sample was filtered, diluted with acetone and analyzed with GC and GCMS.

Materials

All materials were purchased from Sigma-Aldrich in ≥98% purity unless otherwise stated. The materials were used as received except for tetrahydro-3,4-epoxyfuran which was bought from Combi-Blocks. 3,4-hexanediol had already been prepared as earlier reported.[68] The vanadium-based catalysts $(Bu_4N)(dipic)VO_2$[66] and $(Bu_4N)_3[H_3V_{10}O_{28}]$[96] were prepared according to literature.

2-Ethyl-1,2-butanediol: Prepared by a Sharpless dihydroxylation[97] of 2-ethyl-1-butene, which was prepared by the Wittig reaction[98] of 3-pentanone with $Ph_3P=CH_2$ as reported in literature.[99] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 3.42 (s, 2H), 1.48 (m, 4H), 0.85 (t, 6H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ 75.3, 67.4, 27.6, 7.8.

cis-1,2-Cyclooctanediol: Prepared by Sharpless dihydroxylation[97] of cyclooctene. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 3.89 (d, 2H), 2.34 (s, 2H), 2.13 – 1.17 (m, 12H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ 73.3, 30.2, 26.4, 23.9.

3-Isopropoxy-1,2-propanediol: Prepared by ring opening of glycidyl isopropyl ether as described in literature.[100] ^{1}H NMR (D_2O, 400 MHz): δ 4.70 (s, 2H), 3.72 (m, 1H), 3.63 (m, 1H), 3.57 – 3.24 (m, 4H), 1.08 (d, 6H). $^{13}C\{^1H\}$ NMR (D_2O, 100 MHz): δ 73,0, 70.7, 68.7, 62.7, 21,0.

1,4-Anhydrothreitol: Prepared by ring opening of tetrahydro-3,4-epoxyfuran as described in literature.[101] ^{1}H NMR (DMSO-d_6, 400 MHz): δ 4.95 (s, 2H), 3.99 – 3.86 (m, 2H), 3.78 (m, 2H), 3.55 – 3.41 (m, 2H). $^{13}C\{^1H\}$ NMR (DMSO-d_6, 100 MHz): δ 76.9, 73.5.

1-Isopropoxy-2-hexanol: Prepared by ring opening of 1-epoxyhexane with isopropanol and catalyzed by $Er(OTf)_3$ as reported in literature.[102] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 3.79 – 3.52 (m, 2H), 3.52 – 3.36 (m, 1H), 3.19 (dd, 1H), 2.31 (br, 1H), 1.62 – 1.22 (m, 6H), 1.16 (d, 6H), 0.90 (t, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ 72.7, 72.2, 70.6, 33.0, 27.9, 22.9, 22.2, 14.2.

*rac-1-Phenyl-1,2-propanediol***:** Prepared by reduction of 1-phenyl-1,2-propanedione with $NaBH_4$ as reported in literature.[103] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.41 – 7.25 (m, 5H), 4.68 (d, 1H), 4.02 (m, 1H), 2,10 (s, 2H), 1.09 (d, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ 140.4, 128.5, 128.0, 126.8, 77.7, 71.4, 17.5.

cis-2,3-norbornanediol: was prepared by Sharpless dihydroxylation[97] of norbornylene. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 3.68 (d, 2H), 3.05 (br, 2H), 2.13 (m, 2H), 1.75 (m, 1H), 1.57 – 1.35 (m, 2H), 1.17 – 0.96 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ 74.9, 43.2, 31.7, 24.6.

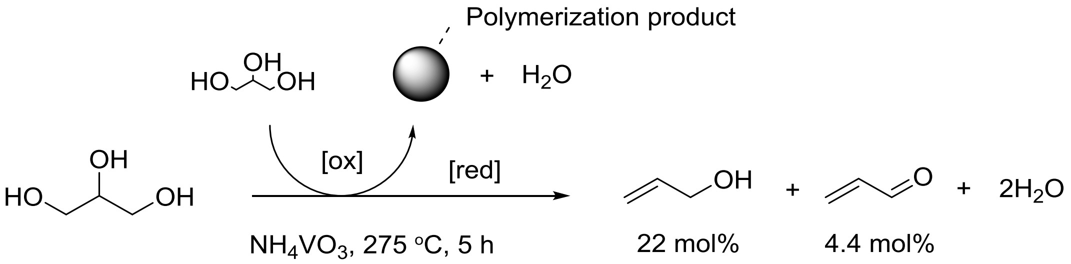
3 Vanadium Catalyzed Reactive Distillation of Glycerol to Allyl Alcohol and Acrolein

3.1 Introduction

With the growing production of biodiesel by transesterification of vegetable oils and animal fats, increasing amounts of the byproduct glycerol, is produced. In this process roughly 10 wt% of the total outcome is glycerol [104] and even though it has some applications in the food- and pharmaceutical industries, a huge overproduction of the compound is taking place. It is therefore important to develop new catalytic pathways for the conversion of glycerol into valuable chemicals.

Lots of research have been conducted in this field, where glycerol has been converted into a wide range of different products and the science reviewed extensively.[22,23,105] One particularly interesting group of related compounds obtained from glycerol is: allyl alcohol[54] (polymerization precursor[106]), acrolein[107,108,109] (production of methionine, 1,3-propanediol[26]) and high-value acrylic acid[110,111] (production of acrylates, polyacrylates[112]). Allyl alcohol and acrolein can be oxidized into acrylic acid, thus discovering new efficient catalytic methods to produce either of them from glycerol is very interesting. The oxidation of acrolein to acrylic acid is well known and done on an industrial scale.[113,114] As for allyl alcohol, Li Xiukai and Zhang Yugen,[115] showed that it can be converted into acrylic acid over a silica supported Mo-V-W-O multiple-metal oxide catalyst in 90% yield. The alcohol was however, obtained from the effective but stoichiometric reaction between formic acid and glycerol.[47]

In addition to the DODH of glycerol, as described in the previous chapter, there are some other ways to convert glycerol to allyl alcohol. Some research groups have conducted flow-bed experiments at >300 °C in which glycerol itself functions as the reductant. As such, iron oxide[116] (Fe_2O_3) and K/Al_2O_3-ZrO_2-FeO_X[117] in flow bed reactors have been able to convert glycerol into allyl alcohol in approximately 25% yield. Reactive distillation experiments on neat glycerol have also been tested. Mészáros *et al.* [118] converted 72% of glycerol into allyl alcohol with 60% selectivity at 220-225 ˚C, under reduced pressure and using a Ni-Mg-Al-hydrotalcite catalyst. Yi *et al.*[119] reported on MTO-catalyzed reactive distillation of glycerol to give 74% of volatile products (calculated for half the amount of initial glycerol, because the other half stays in the reaction flask as oxidized products) with a 1:0.22:0.15 ratio between the formed allyl alcohol, acrolein and



Scheme 25. Reactive distillation in neat glycerol

propanal, respectively. Unfortunately, they did not report how much of the volatile products that are constituted by water, and it is therefore impossible to determine a correct yield of allyl alcohol.

A novel protocol to produce allyl alcohol from glycerol in a reactive distillation setup with NH_4VO_3 as the catalyst, is reported here (Scheme 25). Different reaction conditions have been tested and allyl alcohol yields up to 22 mol% have been found, along with a small amount of acrolein. Glycerol is also the reductant in this solvent free system and is thereby oxidized to compound(s), that quickly polymerizes to high-boiling side products that allow separation of the reduced compounds solely by distillation. A comparison of the catalytic performances between $MeReO_3$ (MTO), $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$ (AHM) and NH_4VO_3 is also reported.

3.2 Results

3.2.1 Optimization of Catalyst and Distillation Setup

The initial experiments were conducted by Johannes R. Dethlefsen. He found that vanadium catalyzes the reduction of glycerol to allyl alcohol, under neat conditions and in a distillation setup, when exposed to extensive heating by a very hot heating mantle (≥290 °C). Different vanadium compounds and additives were tested and results for some of them are reported in Table 16. As was uncovered in the DODH experiments, almost all of the tested vanadium species ended up with the same product yields. The only exception to this rule, was Na_3VO_4 which also gave low yield in the DODH of 1,2-decanediol described in the previous chapter. Addition of the base, $NaHCO_3$, to NH_4VO_3 resulted in a lowered yield of allyl alcohol and supposedly also faster polymerization, since the experiment was stopped after only 2 hours. When citric acid was added, the reaction was found to give product yields similar to those obtained without any acid.

Table 16. Test of Different Vanadium Catalysts and Additives. [a]

Catalyst	Additive	Time [h]	Yields [wt%] of		Yields [mol%] of	
			Vol. prod.	Cond. prod.	Allyl alcohol	Acrolein
NH_4VO_3		4	81	64	22	4.2
V_2O_5		4	81	66	21	4.9
$VO(acac)_2$		5	82	64	19	4.6
Na_3VO_4 [b]		2	61	50	11	0.6
NH_4VO_3	$NaHCO_3$ [c]	2	63	53	12	~0
NH_4VO_3	citric acid [d]	3.5	85	69	22	5.1

[a] Results obtained by Johannes R. Dethlefsen. Reaction conditions A, but the temperature of the heating mantle was controlled by a power regulator (≥290 °C) and a normal distillation setup was used. The reaction was stopped when the magnetic stir bar, could not stir the mixture any longer. Both yields were determined by NMR with 1,4-dioxane as reference. [b] purity ≥90%. [c] 1.7 mol% was added. [d] 1 mol% was added.

It was decided to optimize the distillation setup and temperature control. A new setup was tested after having confirmed the reproducibility of the initial results and certified that glycerol does not decompose, even if left for 2 hours at 280 °C. The heating mantle was exchanged for an aluminum block in which the thermometer controlling the heat was placed, and a short-range distillation mount was used instead of the traditional 13 cm condenser. The aim of the experiment was to test the reaction at a lower temperature and with a more accurate temperature control, thus hopefully remove the products more quickly as a consequence of the shorter condenser. Even though the desired reaction is slow at 250 °C, the short-range setup was found to readily separate glycerol from the products. It was not possible to heat the aluminum-block beyond this temperature however, and the subsequent experiments were therefore conducted in a heating mantle filled with sand. The reaction flask and thermometer were carefully tucked into the sand and the mantle controlled by a power regulator. To gain an approximate value for the temperature inside the reaction mixture, without having to have a thermometer inside it, a graph was created that connects the temperature in the sand with the temperature within a batch of neat glycerol at different power output from the regulator. In the following experiments, the reaction flask and neat glycerol was heated at a chosen power output for approximately 2 hours. At that time the temperature in the sand, and in the glycerol (denoted °C*), was measured and compared with the graph mentioned above. Then 1 mol% NH_4VO_3 was added to the glycerol and the short-range distillation setup put on top of the reaction vessel.

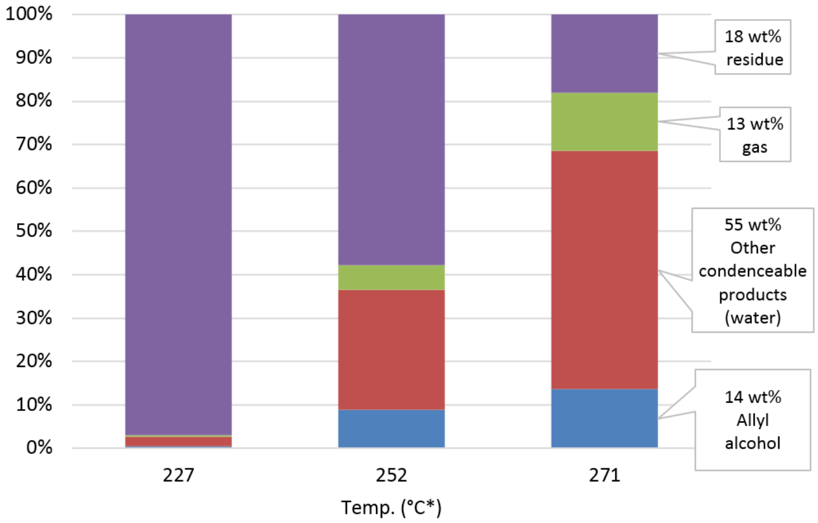


Figure 38. Distribution of products obtained at different temperatures, expressed as wt% of the initial amount of glycerol. Reaction conditions B.

The first experiments conducted in this way gave 22% allyl alcohol after 8 hours at 271 °C*. When the same experiment was done with the 13 cm condenser, only 7% of allyl alcohol could be obtained. These results clearly illustrate that the short-range distillation setup allows for an easier separation of the products, which could give less time for the products to take part in polymerization reactions. This is in good agreement with Mészáros *et al.*[118] who performed their reactive distillation under reduced pressure, probably for the same reason.

An investigation of the necessary reaction temperature using the mantle/sand setup showed almost no production of allyl alcohol at 227 °C* after 8 hours (Figure 38). Even though the allylic alcohol could also be obtained at 252 °C*, a better yield was found when the mixture was heated more to 271 °C*.

The same protocol was also used to test the catalyst amount and time of addition (Table 17). Only 8% allyl alcohol was collected with 0.1 mol% NH_4VO_3 whereas increasing the catalyst loading

Table 17. Changing Catalyst Amount and Time of Addition. [a]

Catalyst [mol%]	Vol. prod. [wt%]	Cond. Prod.[wt%]	Allyl Alc. [mol%]
0.1	28	24	8
1	83	69	22
2	80	66	23
1 [b]	78	65	22

[a] Reaction conditions B. [b] The catalyst was added from the beginning.

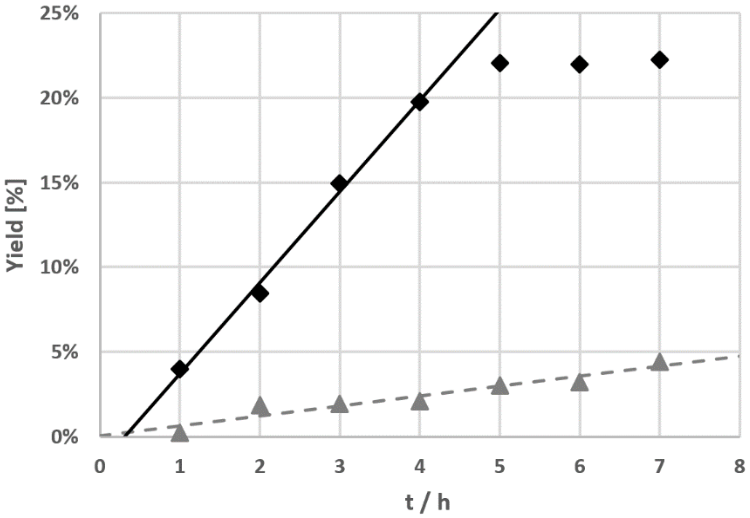


Figure 39. Product evolution for the conversion of glycerol into allyl alcohol (♦) and acrolein (▲) at 275 °C. Reaction conditions A were employed.

from 1 to 2 mol% gave a much more rapid reaction, but only slightly more of the product. If the catalyst was added before heating up the glycerol or after the desired temperature had been reached, was found to have no influence on the final yield.

Regulation of the reaction temperature was however still inaccurate, and it was therefore decided to build a home-made controller to measure the temperature inside the glycerol, while also controlling the heating mantle. A diagram of the electrical circuit is depicted in Figure 43, in the experimental section, followed by the corresponding code. Once constructed, it was possible to control the temperature much more precisely which allowed for easier comparison of the results.

3.2.2 Product Evolution and Comparison to Mo and Re Based Catalysts.

With the setup established (reaction conditions A), it was decided to take a closer look at the product evolution. A series of experiments with different timespans were conducted and the results are summarized in Figure 39. The formation of allyl alcohol increases linearly within the first 4 hours and then it stops. Water and acrolein however, continues to evolve until there is nothing, but a black solid left in the reaction flask. The fact that water is produced until the end, is probably due to polymerization reactions of some high boiling compounds that cannot escape the thick oily residue that later solidifies. It is interesting that the amount of acrolein keep on rising, even after the production of allyl alcohol has ceased. For this reason, the two products are likely to be the result of two different reactions and are probably not being converted into one another by oxidation or reduction mechanisms.

Experiments aimed on resolving the composition of the formed gasses have also been performed. Initially, it was believed to be a mixture mainly constituted by propene. That was because calculations on the mass balance for carbon and oxygen, showed that the residue, allyl alcohol and other condensable products (assumed to be water) could account for all the initial oxygen, but not the carbon. The first experiment aimed at detecting propene by leading the gasses through a solution of Br_2 in dichloromethane, showed a small amount of 1,2-dibromopropane in the GC spectrum. However, later attempts to reproduce the results have failed and it is therefore doubtful that propene should be a major component in the formed gasses.

In an attempt to prove whether the formed gas contains a lot of CO_2, an experiment was conducted in which it was led through a solution of 3-aminopropyltrimethoxysilane (2.8 mmol) in THF (20 ml). The amine is known to react with CO_2 to give a white precipitate and the test experiment gave a positive result shortly after the first bubbles had appeared.[120] Some of the formed gasses are therefore likely to be CO_2, though it was later realized that the small amount of carbon dioxide in the air is enough to give the precipitate when standing for a while in the fume hood. It is also possible that the gas contains some carbon monoxide, but no experiments have been performed to verify it.

Additional information about the ongoing reactions was obtained when it was conducted under laboratory air and nitrogen. The gas was led into the reaction mixture through a glass pipe with a sintered head to allow good dispersion of the gas and with a flowrate so high that glycerol appeared

Table 18. Comparison of V, Re and Mo In the Reactive Distillation of Glycerol. [a]

Catalyst	Temp. (°C)	Time [h]	Yields [wt%] of		Yields [mol%] of	
			Vol. prod.	Cond. prod.	Allyl alcohol	Acrolein
NH_4VO_3	275	4	87	71	22	3.7
$MeReO_3$	170	3	53	49	17	6.4
AHM [b]	236	7	58	51	12	1,4
AHM + base [c]	250	4	81	81	11	1.4

[a] Reaction conditions A on half scale [b] $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ [c] 3 equivalent n-Bu_4NOH to Mo was added (1M in methanol).

in the distillate afterwards. The experiment with nitrogen showed no allyl alcohol production, whereas laboratory air gave rise to a signal in the GC spectrum of the distillate (Figure 42). The residue was transferred into 40 ml of methanol under vivid stirring and GC the spectra recorded. It is clearly seen from the spectra in Figure 42, that the reaction needs to be conducted under oxygen. However, the results are hard to understand as there is no obvious reason for oxygen to be a crucial component in the reaction. With allyl alcohol, acrolein and maybe a small amount of propene being formed, there seems to be little need for one more oxidant.

Re, Mo and V were compared in the reactive distillation of glycerol on half scale and the results are shown in Table 18 (11.5 g glycerol, 25 ml reaction flask). With the temperature control in place it was possible to turn up the heat until the reaction started and products were collected. $MeReO_3$ (MTO) was found to catalyze the reaction at only 170 °C which is the lowest reaction temperature for the three metals. Only 3 hours of reaction time was possible with MTO, because at that point, the black residue was so thick that the experiment had to be stopped. The lowest yields of allyl alcohol were obtained when AHM catalyzed the reaction, even in the case where the base, *n*-Bu_4NOH, was added. It was a surprise that NH_4VO_3 gave a higher yield of allyl alcohol than MTO and AHM + base, because the two latter usually perform better in DODH reactions. Also, when 2,3-dihydroxynaphthalene was added to the deoxydehydration of 1,2-hexanediol (Table 11), an increased yield of 1-hexanol was observed. However, when 1.5 equivalent of the additive to vanadium was used in the reactive distillation, there was no observable difference compared to the results obtained without the additive. It may indicate that another mechanism than DODH, is leading to the formation of allyl alcohol.

3.2.3 The Black Residue

A precise determination of the black solid that is left in the reaction flask after 8 hours of distillation at 275 °C according to reaction conditions A, has been unsuccessful so far. Matrix-assisted laser desorption/ionisation high resolution mass spectroscopy (MALDI-HRMS) was tried, but did not show anything else than the applied matrix (2,5-dihydroxybenzoic acid and trifluoroacetic acid). Powder diffraction could not be done because the solid is not crystalline enough and IR spectroscopy resulted in a straight line. The only method that gives useful and reliable results is the elemental analysis (Table 19). The black solid was washed twice with 40 ml THF, pulverized and found to constitute C: 70.4, H: 7.1 wt% and did for this reason not fit with the

Table 19. Elemental Analysis of the Discussed Solids.

Exp.	Description	Composition of residue [w%]		
		C	H	N
1	Distillation of glycerol for 8 h. at 275 °C (reaction conditions A.)	70.4	7.1	0.1
2	Distillation of 1,3-dihydroxyacetone dimer.	56.5	5.5	0.0
3	Synthesized poly(acrolein)	58.7	8.0	0.0
4	poly(acrolein) heated to ~275 °C	75.5	7.9	0.0

polymer that Yi reported for Re-catalyzed reactive distillation of glycerol.[119] They envisaged a polymer formed from dihydroxyacetone with the theoretical composition C: 50.0, H: 5.6 wt%, which is too far from the values obtained here. A test experiment at 150 °C with 1,3-dihydroxyacetone dimer in the reaction flask, instead of the glycerol, gave a black solid that was washed twice with 40 ml of THF, pulverized, and analyzed to contain C: 56.5, H: 5.5 wt%. For this reason, it seemed unlikely that the polymer should be formed from dihydroxyacetone. Instead, poly(acrolein) seemed to be more reasonable, because the monomer has been detected and has a theoretical composition of C: 64.3, H: 7.2 wt%, which is closer to what was obtained for the black solid. Acrolein (≥95% pure, with 0.2% hydroquinone and 3% water for stabilization) was therefore distilled under nitrogen, at 60 °C, and collected by a water condenser. An NMR spectrum of the monomer was collected (Figure 40) and found to contain only a small amount of acetaldehyde. Then it was left to polymerize, at 57 °C, for 22 hours, after addition of 0.1 mol% benzoyl peroxide. The resulting white precipitate was dried under vacuum at 40 °C, to give the polymer in 29 w% yield (C: 58.7, H: 8.0 wt%). It was not possible to find any type of NMR solvent able to dissolve the polymer, but the IR spectrum fitted well with a reference from the BioRad/Sadtler IR Data collection (Figure 41).

The poly(acrolein) was treated in two different ways. One part of it was put in a round bottomed flask without anything else than the stir bar, but otherwise treated according to reaction conditions A, for 6 hours. The resulting solid, had many different colors, but was also washed with THF, dried, and pulverized to a fine powder (C: 75.5, H: 7.9 wt%). It is evident from the elemental analysis that the reaction temperature is high enough to make the polymer dehydrate, and reach a carbon content, that is higher than what was found for the black powder obtained in the standard experiment. For this reason, the black solid might be a polymer mainly built from acrolein units and maybe some other monomer, possibly glycerol and allyl alcohol. However, this conclusion also opens up for the possibility that the solid obtained from treatment of 1,3-dihydroxyacetone dimer might also be able to further dehydrate as well.

The poly(acrolein) described above, was produced by radical polymerization of the monomer. An experiment with an added radical scavenger was therefore performed to see if the polymerization, in a normal experiment, could be slowed down or even stopped completely. A round bottomed flask was charged with glycerol, NH_4VO_3, and 5 mol% 2,6-di-*tert*-butyl-4-methylphenol (BHT) for scavenging the radicals (reaction conditions A, 250 °C). The reaction temperature could not be raised to 275 °C because of the boiling point of BHT, yet the desired distillation was known to happen at 250 °C as well (Figure 38). After 8 hours of distillation, 12 mol% of the initial glycerol was collected as allyl alcohol, which increased to 20 mol% after an additional 7 hours. The final result is therefore close to what is obtained in 5 hour experiment at 275 °C. The black residue that was left in the reaction flask, had probably become a solid, if the polymer had had more time to dehydrate. Residues from the short-time experiments in Figure 39 had already been investigated thoroughly, but no other compounds than glycerol could be identified.

It is possible that the polymerization could be partly avoided if the reaction was performed in a solvent. The only problem is that the scope of suitable solvents is rather narrow because of the high boiling point that it must have. However, reactive distillation of glycerol (2.5 g), catalyzed by 1 mol% NH_4VO_3 and mixed in 25 g of 18-crown-6-ether (bp. 396 ± 37 °C), was performed at 275 °C for 5 hours. Afterwards, only 10 mol% allyl alcohol and 0.5 mol% acrolein was found in the collection flask at which point the residue had become dark and viscous. It was considered unnecessary to repeat the experiment with a longer reaction time, because the yield was low, and the polymerization still seemed to be ongoing.

Another attempt to use a solvent in the distillation, involved the completely non-polar triphenylmethane (bp. 358–359 °C). It was thought possible that the catalyst and maybe even some intermediate byproducts, would be soluble in this solvent even though glycerol itself would definitely form a two phase system. The substrate (23 g) was added by a syringe pump to a mixture of triphenylmethane (50-60 ml) and $VO(acac)_2$ (2 mol%) that was heated to 275 °C. In the beginning of the experiment, the flowrate was only 1 ml/h because the mixture spluttered violently, yet it was later raised to 4 ml/h when the spluttering ceased. After a total of 8 hours at the reaction temperature, the distillate was found to contain 16 mol% allyl alcohol and 3.3 mol% acrolein. Again, the black residue was investigated, but without giving valid clues towards any intermediate byproducts.

3.3 Conclusion

Reactive distillation of glycerol with vanadium has been investigated. Only 1 mol% NH_4VO_3 is enough to achieve up to 22 mol% of allyl alcohol and 4 mol% acrolein from 23 g of glycerol, when heated to 275 °C for 5 hours. This is done in an optimized setup in which a short-range distillation centerpiece allows for a fast separation of the alcohol. If the catalyst was added before or after heating up the glycerol, or in larger amounts (2 mol%), did not make any significant difference to the final outcome.

The evolution of acrolein was found to continue long after the formation of allyl alcohol had ceased, and the two products are therefore expected to be formed in two separate reactions. Also, experiments have shown that the gasses, that are formed during the distillation, are likely to be CO_2, and CO, and maybe an insignificant amount of propene.

Comparison of MTO, AHM, and NH_4VO_3 showed that the vanadium catalyst gives the highest yield of allyl alcohol. This is a surprising since Re and Mo tend to display a higher activity for the DODH reaction than V does.

Measurements aimed at identification of the black residue that is left in the reaction flask have been unsuccessful so far. This is mainly because it has been impossible to find a solvent that is able to dissolve the formed polymer. Instead, it was decided to try and make the polymer from reactive compounds that might be formed during the distillation. One such compound is dihydroxyacetone, which was bought as the dimer and then allowed to polymerize to a solid. Acrolein, was distilled and polymerized as well, but was afterwards heated to the temperature used in the distillation experiments. This gave a dehydrated polymer with a carbon content a bit higher than what was measured for the black residue collected after a distillation experiment. It is therefore possible that the left-over in the reaction flask is a polymer mainly built from acrolein monomers However, it is still uncertain whether the solid formed from 1,3-dihydroxyacetone dimer is able to further dehydrated at 275 °C to reach the same carbon content as well.

A few attempts was done to use a solvent in the distillation as that would probably impede the polymerization reactions. However, when performing the distillation in 18-crow-6-ether, only 10 mol% allyl alcohol was obtained after 5 hours along with a black and viscous residue. Also, when slowly pumping the substrate into a mixture of $VO(acac)_2$ in triphenylmethane, only 16 mol% allyl alcohol was collected after 8 hours at 275 °C.

The results on V-catalyzed reactive distillation of neat glycerol, that has been described in this chapter, clearly illustrate that V catalysts are at least competitive to those based on Re and Mo. Even though the required reaction temperature is much lower for rhenium, this element is also much more expensive and vanadium is therefore an interesting substitute. The V-catalyzed distillation has proven that it is able to give yields of allyl alcohol that are almost equal to the results reported for flow-bed reactors, while it operates at lower temperatures.

A suggestion to further optimize the reaction conditions and possibly gain more knowledge about the ongoing reactions, is to perform the reaction under an atmosphere with a raised concentration of oxygen. This would hopefully give some clues about the role that oxygen plays during the distillation. Also, the polymer that may be created from 1,3-dihydroxyactone dimer should probably be exposed to the reaction conditions, to see if it is able to dehydrate and reach a carbon content equal to the one found for the solid obtained after a normal distillation. The research on reactive distillation of neat glycerol could also be expanded to other elements than those tested herein or even onto mixtures of different metals.

3.4 Experimental Section

Instrumentation and Materials

The GC, GCMS and NMR instruments used to investigate the reactive distillation of glycerol, is the same as what was described for the study on vanadium catalyzed DODH.

The FT-IR spectra was measured on a Bruker Alpha-P instrument, equipped with a platinum attenuated total reflection module.

Elemental analysis was performed in Germany by the Mikroanalytischen Laboratorium Kolbe.

Reaction Conditions A

A 50 ml round bottomed flask was mounted with the short-range distillation setup and the cooling water connected. The temperature control was put in through a secondary connection on the distillation setup and fitted so that the tip of the thermometer did not disturb the magnetic stirring, nor did it touch the side of the reaction flask. The heating mantle was controlled by the home-made temperature control. 23 g (250 mmol) of glycerol (Sigma-Aldrich ≥ 99.5%) and 1 mol% NH_4VO_3 were added to the reaction flask, the time was started, and the mixture heated to the desired temperature. The yield of acrolein was determined by NMR with 1,4-dioxane as reference, whereas allyl alcohol was determined on the GC with THF as the reference, and diluted with methanol.

Reaction Conditions B

A 50 ml round bottomed flask (B14) was filled with 23 g glycerol (Acros Organics 99+%), then mounted with the short-range distillation setup and the cooling water connected. A heating mantle, which was controlled by a voltage regulator, was filled with sand and the reaction flask and an electronical thermometer lowered into it. The sand was warmed up until the temperature had stabilized at the point that corresponded to the desired reaction temperature within the glycerol (~2 h.). Then, 1 mol% NH_4VO_3 was added quickly and the time started. After 8 hours, the yield of allyl alcohol was determined on the GC with THF as the reference, and diluted with methanol.

Materials

Methyltrioxorhenium (MTO) was bought from Strem Chemicals in 98% purity, while all other materials were purchased from Sigma-Aldrich in ≥98% purity unless otherwise stated.

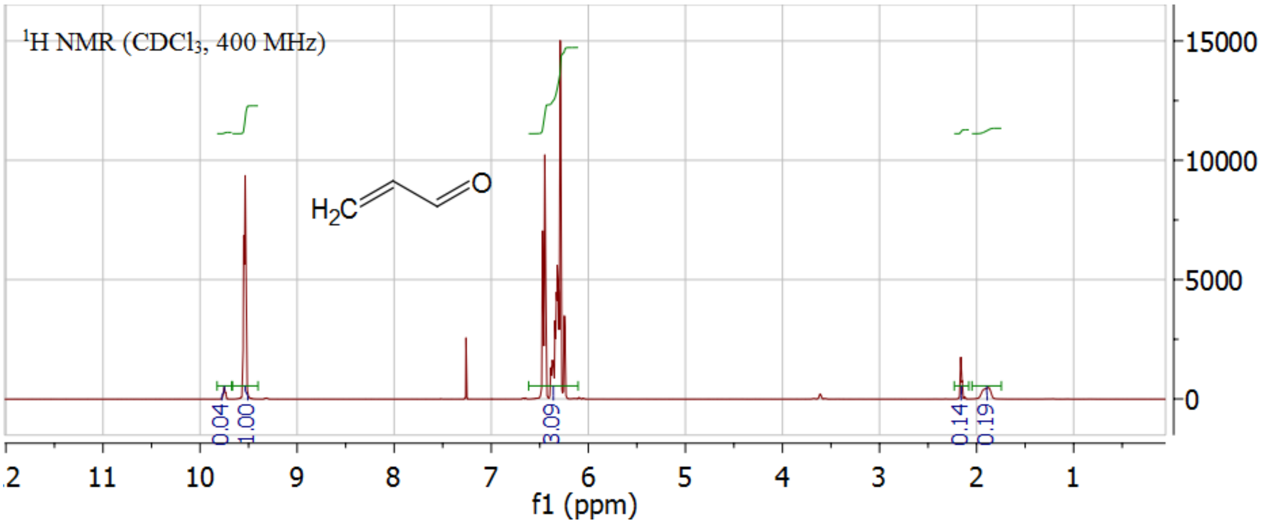


Figure 40. Acrolein after distillation under N_2.

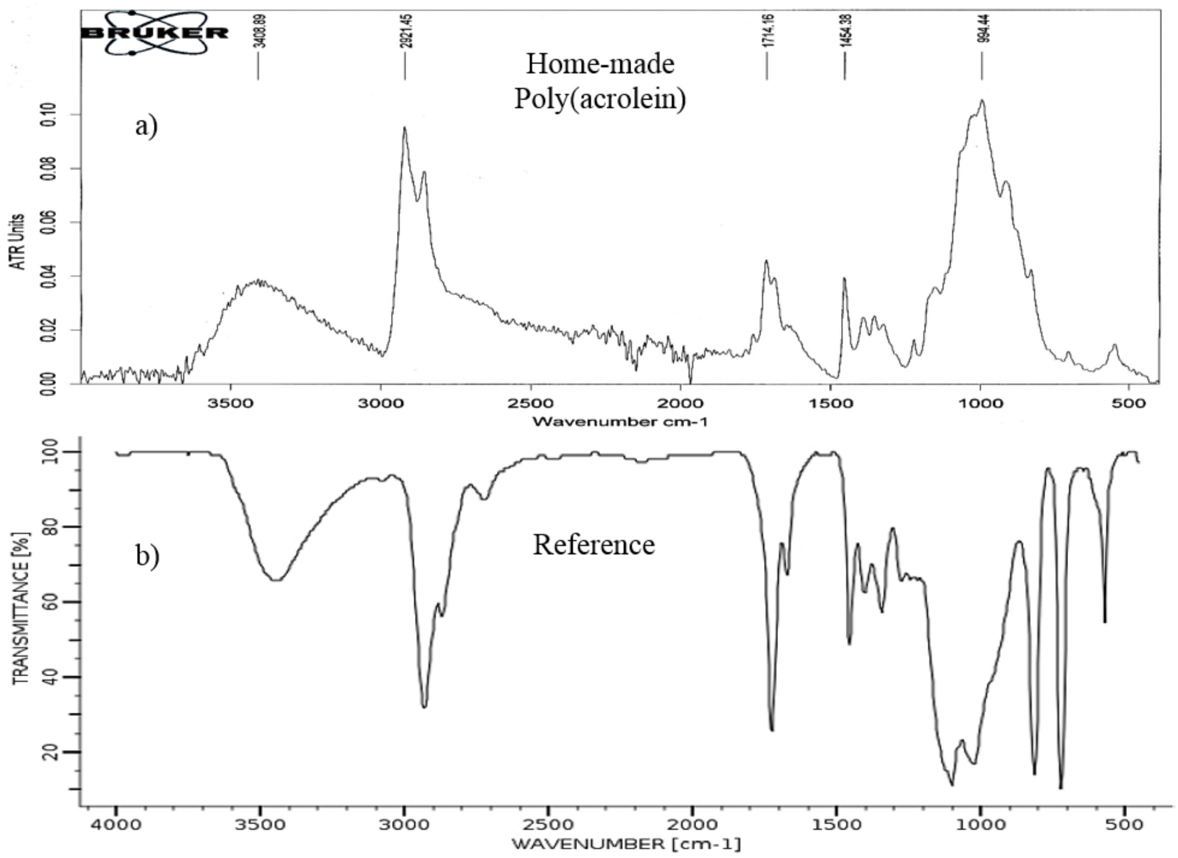


Figure 41. IR spectra of poly(acrolein). The reference was found on SciFinder and originate from the BioRad/Sadtler IR Data collection.

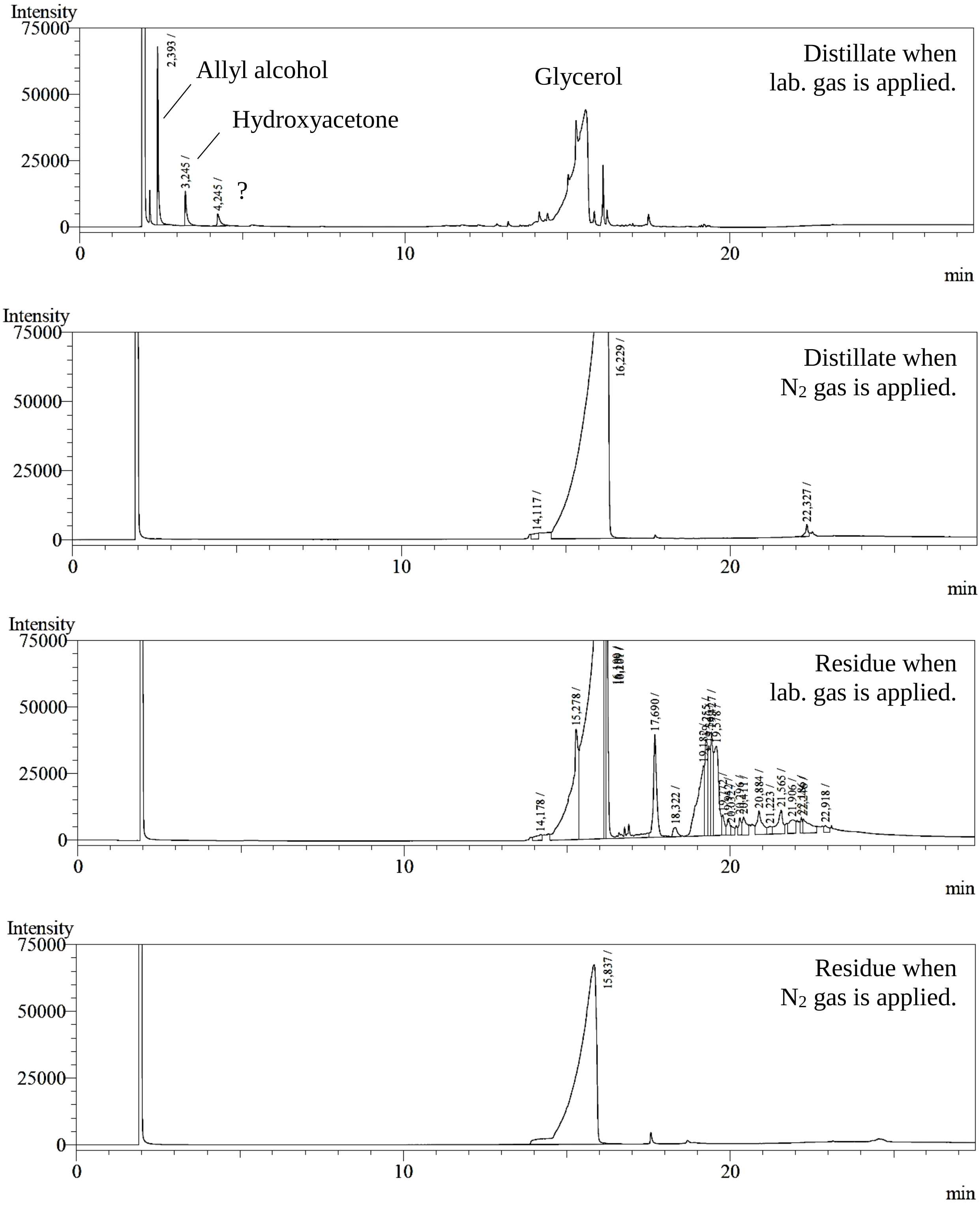


Figure 42. GC spectra obtained from the experiments where laboratory air and N_2 gas was bubbled through the reaction mixtures.

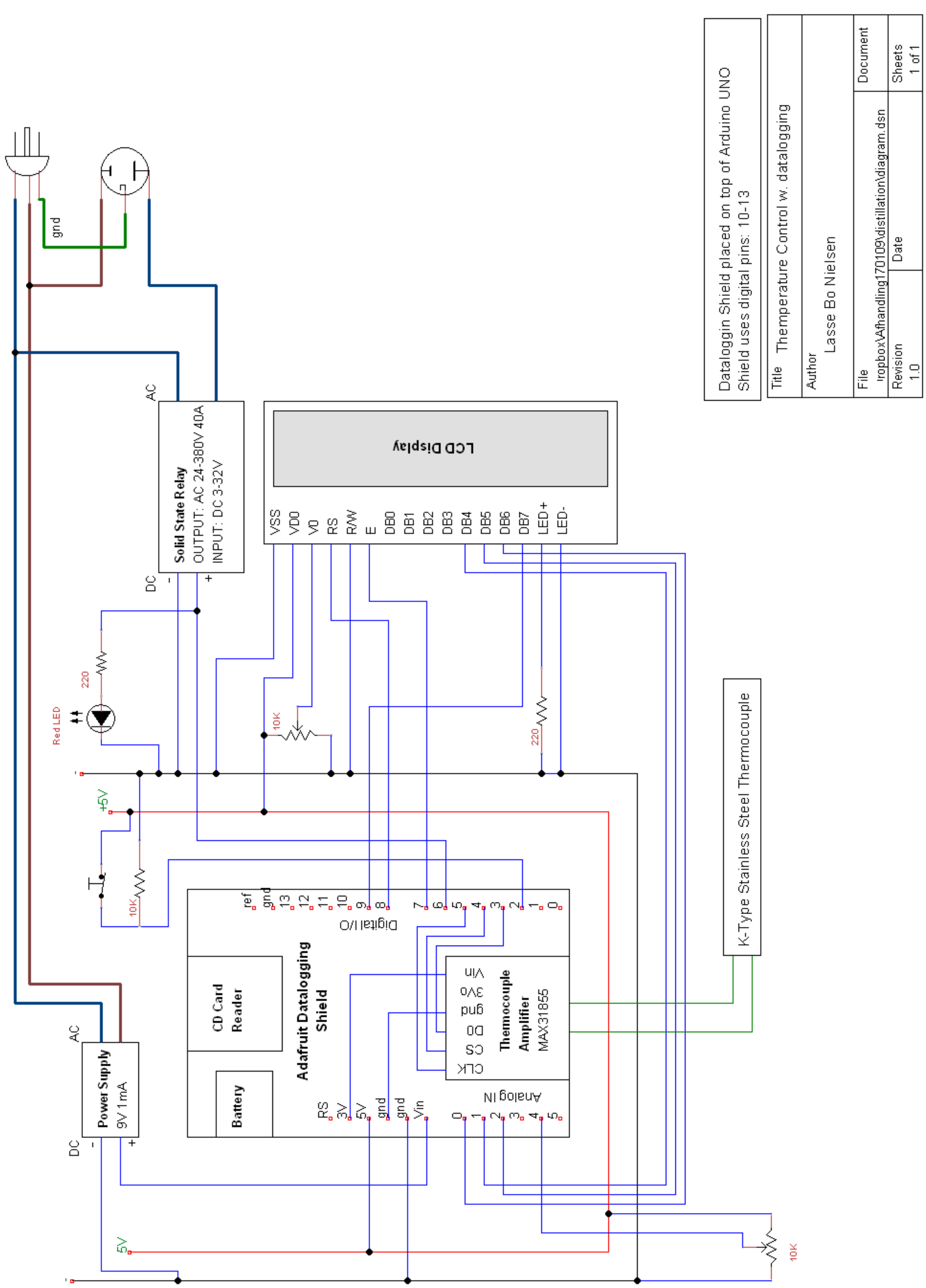
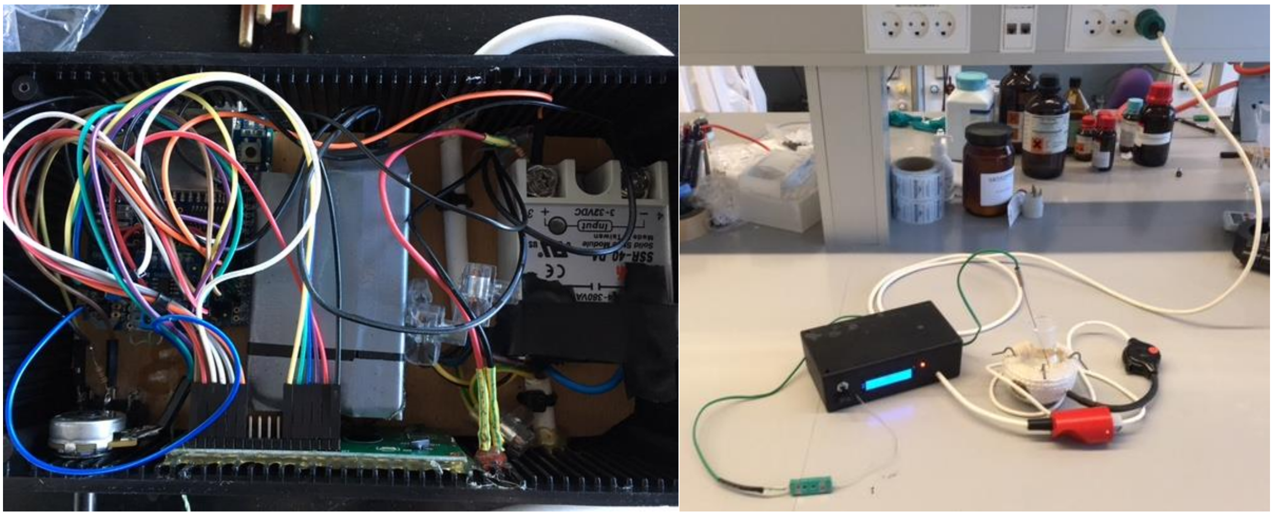


Figure 43. Schematic diagram of the home-made temperature control.



Code for The Temperature Control.

```
#include <LiquidCrystal.h>
LiquidCrystal lcd(8, 7, 15, 16, 14, 9);
#include <Adafruit_MAX31855.h>
#include <SPI.h>
#include <SD.h>
#include <Wire.h>

#define SYNC_INTERVAL  60000 // mills between calls to flush() - to write data to the card. #define substitutes all instances of the name with whatever comes after the name, when compiling.

#define screenupdate_interval  500  // Read temperature every..

const int ECHO_TO_SERIAL = 0; // echo data to serial port
uint32_t syncTime = 0; // time of last sync() to SD Card.
uint32_t screentime = 0; // time of last screen update.
uint32_t startTime = 0 ;

const int chipSelect = 10; // for the data logging shield, we use digital pin 10 for the SD cs line
const int tempPot = A4;
const int switchPin = 2;
const int relayPin = 6;
int switchState = 0;
int tempPotVal = 0;
int temp = 0;
int SDhere = 0; // Is there a SD Card.
double c = 0; // temperature reading.

// the logging file
File logfile;
// ---- thermocouple with SPI on any three digital pins -------
```

```
// Example creating a thermocouple instance with software SPI on any three
// digital IO pins.

int thermoDO = 3;
int thermoCS = 4;
int thermoCLK = 5;

Adafruit_MAX31855 thermocouple(thermoCLK, thermoCS, thermoDO);
void error(char *str){
Serial.print("error: ");
Serial.println(str);
while(1);
}

void setup() {
// put your setup code here, to run once:

Serial.begin(9600);
lcd.begin(16,2);
pinMode(10, OUTPUT);
pinMode(2, INPUT);
pinMode(6, OUTPUT);

lcd.print("Initializing"); lcd.setCursor(0,1); lcd.print("SD card...");
delay(3000);

    if (ECHO_TO_SERIAL == 1){
        Serial.print("Initializing SD card...");
    }

// see if the card is present and can be initialized:
if (!SD.begin(chipSelect)) {
  lcd.clear(); lcd.setCursor(0,0); lcd.print("No SD card found");
  delay(5000);

    if (ECHO_TO_SERIAL == 1){
    Serial.println("No SD card found");
    }
}
else {
SDhere = 1; // There is a SDcard. Make and then write to a logfile.

lcd.clear(); lcd.setCursor(0,0); lcd.print("SD card"); lcd.setCursor(0,1); lcd.print("Initialized..");
delay(3000);

    if (ECHO_TO_SERIAL == 1){
    Serial.println("card initialized.");
    }
```

```
// create a new file
  char filename[] = "LOGGER00.CSV";
  for (uint8_t i = 0; i < 100; i++) {
    filename[6] = i/10 + '0';
    filename[7] = i%10 + '0';
    if (! SD.exists(filename)) {
      // only open a new file if it doesn't exist
      logfile = SD.open(filename, FILE_WRITE);
      break;  // leave the loop!
    }
  }
if (! logfile) {
  lcd.clear(); lcd.setCursor(0,0); lcd.print("No file created!");
  delay(10000);
  error("couldnt create file");
}

lcd.clear(); lcd.setCursor(0,0); lcd.print("Filename:");
lcd.setCursor(0,1); lcd.print(filename);

    if (ECHO_TO_SERIAL == 1){
    Serial.print("Logging to: ");
    Serial.println(filename);
    }

delay(6000); // give people time to read the filename.
}
// connect to RTC
Wire.begin();

if (SDhere == 1) {
logfile.println("Minutes, T, T set");

    if (ECHO_TO_SERIAL == 1){
    Serial.println("Minutes, T, T set") ;
    }
}

// wait for MAX chip to stabilize

delay(500);
lcd.clear();
lcd.setCursor(0,0);
startTime = millis();
}
```

```
void loop() {
  // put your main code here, to run repeatedly:

 if (SDhere == 1 && ((millis() - syncTime) >= SYNC_INTERVAL)) {
 mylogfunc();
}
switchState = digitalRead(switchPin);
if (switchState == 0){
analogWrite(relayPin, 0);
tempPotVal = analogRead(tempPot);
temp = map(tempPotVal, 0, 1023, 0, 350);
}
c = thermocouple.readCelsius();
if ((millis() - screentime) >= screenupdate_interval){
lcd.clear();
lcd.setCursor(0,0);
lcd.print("C = ");
lcd.print(c);
lcd.setCursor(0,1);
lcd.print(temp);
screentime = millis();
}

if (switchState == 1){
if (c < (temp - 12)){
analogWrite(relayPin, 255);
}
else if (c < (temp - 8)){
analogWrite(relayPin, 230);
}
else if (c < (temp - 6)){
analogWrite(relayPin, 210);
}
else if (c < (temp - 5)){
analogWrite(relayPin, 190);
}
else if ( c < temp - 4){
analogWrite(relayPin, 180);
}
else if ( c < temp - 3){
analogWrite(relayPin, 170);
}
else if ( c < temp - 2){
analogWrite(relayPin, 160);
}
else if ( c < temp - 1){
analogWrite(relayPin, 150);
}
else if (c >= temp){
    analogWrite(relayPin, 0);

    }}}
```

```
void mylogfunc(){

   logfile.print(((millis() - startTime)/SYNC_INTERVAL) + 1);


if (ECHO_TO_SERIAL == 1){
  Serial.print(((millis() - startTime)/SYNC_INTERVAL) + 1);
}

c = thermocouple.readCelsius();

   if (isnan(c)) {
     logfile.println("Something wrong with thermocouple!");
   } else {
     logfile.print(", ");
     logfile.print(c);
     logfile.print(", ");
     logfile.println(temp);
   }

if (ECHO_TO_SERIAL == 1){
   if (isnan(c)) {
     Serial.println("Something wrong with thermocouple!");
   } else {
     Serial.print(", ");
     Serial.print(c);
     Serial.print(", ");
     Serial.println(temp);
   }
}

// Now we write data to disk! Don't sync too often - requires 2048 bytes of I/O to SD card
// updating FAT

syncTime = millis();

    if (ECHO_TO_SERIAL == 1){
    Serial.print("Milliseconds since startup: ");
    Serial.println(syncTime);
    }

logfile.flush();
}
```

4 Publications

Molybdenum-Catalyzed Conversion of Diols and Biomass-Derived Polyols to Alkenes Using Isopropyl Alcohol as Reductant and Solvent

Dethlefsen, J. R.; Lupp, D.; Teshome, A.; Nielsen, L. B.; Fristrup, P.

ACS Catal. **2015**, 5, 3638–3647.

Vanadium-Catalyzed Deoxydehydration of Vicinal Diols using Isopropyl Alcohol as Reductant

Nielsen, L. B.; Larsen, D. B.; Dethlefsen, J. R.; Fristrup, P.

Submitted to *ACS Catal.* Was then rejected and suggested for submission in *Organometallics*.

ACS Catalysis
Research Article
pubs.acs.org/acscatalysis

Molybdenum-Catalyzed Conversion of Diols and Biomass-Derived Polyols to Alkenes Using Isopropyl Alcohol as Reductant and Solvent

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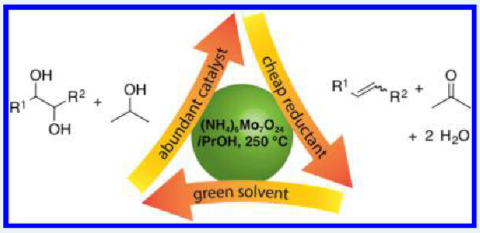
Supporting Information

ABSTRACT: Chemical processes capable of reducing the high oxygen content of biomass-derived polyols are in demand in order to produce renewable substitutes for chemicals of fossil origin. Deoxydehydration (DODH) is an attractive reaction that in a single step transforms a vicinal diol into an alkene, but the reaction requires a homogeneous catalyst, a reductant, and a solvent, which are typically expensive, unsustainable, or inefficient. Herein, we present the use of molybdenum(VI)-based compounds, in particular the cheap and commercially available $(NH_4)_6Mo_7O_{24}\cdot 4H_2O$, as catalysts for the DODH of vicinal diols in isopropyl alcohol (^{i}PrOH), which serves as both the solvent and reductant. The reaction proceeds at 240−250 °C in a pressurized autoclave, and the alkene yield from simple aliphatic diols can be as high as 77%. The major byproducts are carbonyl compounds—formed by dehydration of the diol—and the alcohols formed by transfer hydrogenation of the carbonyl compounds; the total yield of reduced species (i.e., alkene and alcohols) can be as high as 92%. The DODH of glycerol yields allyl alcohol, which undergoes subsequent Mo-catalyzed deoxygenation to propylene driven by the oxidation of ^{i}PrOH; a major byproduct is the homocoupled product 1,5-hexadiene. Further insight in this Mo-catalyzed deoxygenation is gained by an investigation of model compounds: The allylic alcohol 1-hexen-3-ol is deoxygenated to hexene isomers in a yield of 65%, while benzyl alcohol is deoxygenated to toluene in a yield of 93%. The DODH of erythritol yields 39% 2,5-dihydrofuran, while the DODH of the proposed intermediate 1,4-anhydroerythritol yields 75%. The mechanism of the DODH of 1,4-anhydroerythritol was investigated by means of density functional theory (DFT), and the rate-determining step (24.1 kcal/mol) was found to be reduction of a molybdenum(VI) diolate to a molybdenum(IV) diolate.

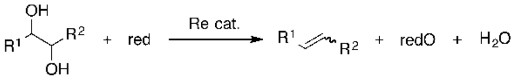


KEYWORDS: *biomass, deoxydehydration, deoxygenation, molybdenum, polyols*

INTRODUCTION

The realization of an economy completely independent of fossil reserves requires not only the exploitation of alternative energy sources but also the development of new processes for the production of organic platform chemicals from renewable feedstocks. Apart from transportation fuels, most petroleum is used for the production of polymers (e.g., polyethylene, polypropylene, polyvinyl chloride, and polystyrene),[1] and it is therefore desirable to find cheap, abundant, and preferably nonedible biomass feedstocks that can be converted into plastic precursors. Notwithstanding the promising prospect of novel platform molecules like lactic acid, 5-hydroxymethylfurfural, and levulinic acid,[2] these compounds are typically formed by redox-neutral processing of biomass, and reactions capable of not only dehydrating but also reducing biomass can serve as a supplement that makes a wider range of biomass-derived molecules available. An abundant motif in biomass is the hydroxyl group that is found both in carbohydrates (obtained from cellulose, hemicellulose, and starch) and glycerol (obtained from triglycerides), and an emerging strategy to reduce the oxygen content of such compounds is to deploy the deoxydehydration (DODH) reaction. This reaction transforms a vicinal diol into the corresponding alkene in a single step; the typical DODH reaction is catalyzed by a rhenium compound and driven by the oxidation of a sacrificial reductant (Scheme 1).[3,4]

Scheme 1. Generalized Rhenium-Catalyzed DODH of a Vicinal Diol into an Alkene Driven by the Oxidation of a Sacrificial Reductant ("red")



In addition to the transformation of a number of model compounds resembling biomass-derived polyols, the rhenium-catalyzed DODH has been employed in the conversion of the sugar alcohol sorbitol (i.e., reduced glucose) into 1,3,5-hexatriene[5] and—in combination with a subsequent hydrogenation—mucic acid (i.e., oxidized galactose) into adipic acid;[5,6] 1,3,5-hexatriene might become a plastic precursor similar to 1,3-butadiene, while adipic acid is already today used as a nylon precursor. Furthermore, the DODH of glycerol yields allyl

Received: February 27, 2015
Revised: April 27, 2015
Published: May 4, 2015

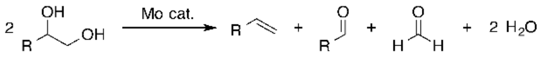
DOI: 10.1021/acscatal.5b00427
ACS Catal. 2015, 5, 3638−3647

alcohol.[5,7] Despite the fact that a major use of allyl alcohol today is in the production of glycerol, the expected gradually lower price of waste glycerol from the manufacture of biodiesel could make the use of allyl alcohol as a plastic precursor economically viable,[8,9] and it has recently been demonstrated that allyl alcohol can be deoxygenated to propylene[10] and that glycerol can undergo hydrodeoxygenation (HDO, i.e., deoxygenation using hydrogen as reductant) to propylene in aqueous solution at 300 °C.[11] The major advantage of the DODH process over the HDO process is the preservation of functionality: The DODH of a vicinal diol yields an *alkene*, whereas the HDO typically yields an *alkane*. Therefore, the latter process has primarily been proposed for the production of biofuels[12−16] and in the processing of the entire lignocellulosic biomass[17−19] and not only the hydrolyzed carbohydrate fractions.

This—for some purposes excessive—hydrogenation of alkenes to alkanes has also been noted by Abu-Omar and coworkers, who observed that the use of the cheap and clean reductant H_2 in the CH_3ReO_3-catalyzed DODH of vicinal diols in thf at 150 °C yielded a mixture of the corresponding alkenes (always <60%) and alkanes.[20] If hydrogen could drive the Mo-catalyzed DODH, hydrogenation of the alkenes could probably be avoided as molybdenum is expected to be a poorer hydrogenation catalyst than rhenium, and this has indeed been observed in the MoO_3-catalyzed HDO of acetone into propylene at 400 °C.[21]

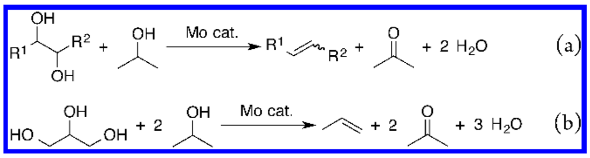
The implementation of the DODH process on an industrial scale is not only hampered by the use of the remarkably scarce element rhenium—which as a byproduct of molybdenum has an extremely volatile price[22]—but also by the use of reductants and solvents that are neither cheap nor green. The highest alkene yields (almost quantitative) have been obtained using the expensive PPh_3 as a reductant, and although Nicholas and coworkers have obtained high yields using the cheaper alternatives Na_2SO_3[23,24] and elemental carbon, iron, zinc, and manganese,[25] these reductants are only efficient in solvents like benzene or chlorobenzene, which are cheap but neither green nor good at dissolving biomass-derived polyols. The use of the secondary alcohols 3-octanol[26] and 3-pentanol[5,6] as both reductants and solvents is promising, but they are relatively expensive, and the solubility of polyols is still low. Shiramizu and Toste[5] attempted to employ ethanol, 1-propanol, and isopropyl alcohol in the CH_3ReO_3-catalyzed DODH of 1,4-anhydroerythritol, but the diol only underwent conversion in 1-propanol and the yield of 2,5-dihydrofuran was low (28%). The efficiency of a number of vanadium-based catalysts has been surveyed by Chapman and Nicholas;[27] notwithstanding the high yields, the use of PPh_3 as a reductant and benzene or chlorobenzene as solvent limits the large-scale applications of the process. The use of molybdenum-based catalysts—and in particular the cheap and commercially available $(NH_4)_6Mo_7O_{24}\cdot 4H_2O$ (AHM)—has also been demonstrated,[28,29] but the only reductant that was able to drive the Mo-catalyzed DODH was the diol itself; that is, half the diol underwent DODH to the corresponding alkene while the other half underwent oxidative deformylation (Scheme 2).[29,30] A cheap diol could have justified sacrificing half of it as reductant—and this strategy has indeed been pursued by Abu-Omar and coworkers[7]—but the oxidative deformylation leads to the formation of aldehydes and inevitably related acetals and polymerization products, which poses a significant problem with respect to product separation and recyclability of the solvent and the catalyst.

Scheme 2. Molybdenum-Catalyzed DODH of a Vicinal Diol into an Alkene Driven by the Oxidative Deformylation of the Diol Itself into Formaldehyde and the Aldehyde with One Less Carbon Atom than the Diol



With the objective of conducting the molybdenum-catalyzed DODH of not only diol model compounds but also the biomass-derived polyols glycerol and erythritol under conditions that could realistically be implemented on an industrial scale, we set out to find a green and cheap reductant capable of outcompeting the diol in reducing the catalyst as well as a green and cheap solvent capable of dissolving large amounts of glycerol or other biomass-derived polyols. In the present work, we show that isopropyl alcohol can be used as both a reductant and a solvent in the AHM-catalyzed DODH of vicinal diols at 240−250 °C in a pressurized autoclave (Scheme 3a) and that the allyl alcohol formed in situ by DODH of glycerol undergoes deoxygenation to propylene (Scheme 3b). In the following sections, an investigation of these two reactions—including tests of other reductants, solvents, and molybdenum-based catalysts—will be presented.

Scheme 3. Molybdenum-Catalyzed (a) DODH of a Vicinal Diol into an Alkene and (b) Sequential DODH and Deoxygenation of Glycerol to Propylene Driven by Oxidation of ^{i}PrOH to Acetone



RESULTS AND DISCUSSION

Test of Hydrogen as Reductant. We had previously observed that AHM catalyzed the DODH of 1,2-tetradecanediol in dodecane according to Scheme 2; using 1 mmol of diol, 5 mol % of AHM (calculated with respect to Mo), and 2 mL of dodecane, the reaction was complete within 1 h at 200 °C.[29] Although none of the tested reductants (PPh_3 and primary, secondary, and benzylic alcohols) were able to outcompete the consumption of the diol itself as the reductant, attempts were made to use H_2.

The viability of using hydrogen as a reductant was initially tested by heating a solution of 1,2-decanediol and AHM in hexane to 247 °C under 22 bar of hydrogen; this reaction is similar to the aforementioned AHM-catalyzed DODH of 1,2-tetradecanediol in dodecane, although the highest attainable temperature in an open system was ∼205 °C. After 12 h, the conversion was complete and 31% of 1-decene (**C═C**) had formed together with 17% of 2-decanone (**C═O**), 2% of 2-decanol (**2°OH**), and 5% of 1-decanol (**1°OH**), that is, a total yield of reduced species (alkene and monohydric alcohols) of 38%, which did not exclude the possibility that the diol itself was oxidized. The reaction was therefore repeated using nitrogen instead of hydrogen, which resulted in the same product distribution (Table 1), thus excluding the possibility that hydrogen was consumed.

Table 1. Comparison of Hydrogen and Nitrogen Gas in the AHM-Catalyzed DODH of 1,2-Decanediol in the Solvents Hexane and ^{i}PrOH[a]

gas	solvent	T_{max} [°C]	yields [%] of			
			C=C	C=O	2°OH	1°OH
H_2	hexane	247	31	17	2	5
N_2	hexane	246	30	19	3	4
H_2	^{i}PrOH	242	49	10	5	15
N_2	^{i}PrOH	242	46	10	6	13

[a] Reaction conditions A were employed (see Experimental Section).

Table 2. Comparison of Solvents in the AHM-Catalyzed DODH of 1,2-Decanediol[a]

solvent	T_{max} [°C]	conv. [%]	yields [%] of			
			C=C	C=O	2°OH	1°OH
MeOH[b]	239	57	17	5	<1	2
EtOH	247	full	37	11	5	10
^{n}PrOH	251	full	36	13	7	11
^{i}PrOH	242	full	49	10	5	15
^{t}BuOH[c]	232	39	~0	~0	~0	~0
3-pentanol	252	full	33	8	5	14
acetone	249	96	11	23	1	~0
hexane	247	full	31	17	2	5
water[d]	241	~0	~0	~0	~0	~0

[a] Reaction conditions A were employed (see Experimental Section) unless otherwise noted; the autoclave was pressurized with hydrogen. [b] Heated for 900 min. [c] Heating stopped after 350 min due to rapidly increasing pressure. [d] The diol was 1,2-hexanediol; heating stopped after 220 min.

As hexane was never intended to be the solvent for the DODH of biomass-derived polyols, the two experiments were repeated in ^{i}PrOH, which is a cheap and environmentally benign solvent that is miscible with glycerol at room temperature. Isopropyl alcohol was initially favored over the even cheaper monohydric alcohols methanol and ethanol because its potential oxidation product acetone would be easy to detect; that said, we had previously shown that the secondary alcohol 3-octanol could not be oxidized in the molybdenum-catalyzed DODH at 200 °C and that its presence was indeed detrimental to the alkene yield.[29] Regardless of the choice of gas, up to 49% of alkene did, however, form, and the total yield of reduced species was above 65% (Table 1), thus excluding the oxidation of not only hydrogen but also the diol. In confirmation of ^{i}PrOH being the reductant, the presence of acetone in the reaction mixture was observed by NMR spectroscopy. The regeneration of ^{i}PrOH by hydrogenation of acetone can proceed with 99.9% selectivity and 99.9% conversion over a Raney-nickel catalyst in the liquid phase;[31] the process has primarily been implemented where excess acetone has been readily available from another process, which would be the case here.

Molybdenum-catalyzed transfer hydrogenation is rare but not unprecedented: the transfer hydrogenation from ^{i}PrOH to 1-hexene catalyzed by the molybdenum(0) complex $Mo(N_2)_2(dpe)_2$ (dpe = $Ph_2PCH_2CH_2PPh_2$) was investigated by Tominaga and co-workers more than 30 years ago.[32−34] The transfer hydrogenation proceeded through the formation of the hydride complex $MoH_4(dpe)_2$, but considering the significantly lower temperatures (only 80 °C) and the fact that the reaction was used for hydrogenation of 1-hexene to hexane, we have no reason to assume that this reaction is related to the DODH reaction by anything else than a common transition metal.

A preliminary optimization of reaction conditions with respect to time, temperature, pressure, and catalyst loading (Table S1) showed that the highest accessible temperature (240−250 °C) was the best; higher temperatures were inaccessible due to limited power and the accelerated degradation of PTFE above 230 °C. The pressure had no influence on yields or product distributions, which was expected due to the inert nature of the employed gases. The reaction time was dependent on the catalyst loading, but we settled for 5 mol % of catalyst and a reaction time of 800 min as the standard conditions (referred to as reaction conditions A, see Experimental Section for details).

Solvent Screening. Although only ^{i}PrOH and presumably the diol itself were found to be able to serve as reductants in the AHM-catalyzed DODH of 1,2-decanediol, the viability of hydrogen as a reductant was tested again in a number of other solvents (Table 2). The simple alcohols MeOH, EtOH, and ^{n}PrOH gave poor alkene yields, and the alkene yield in MeOH was even lower than that in nonoxidizable hexane. The alkene yield in 3-pentanol was comparable to that in the primary alcohols, but as 3-pentanol is neither cheap nor miscible with glycerol, it was not investigated further. The tertiary alcohol ^{t}BuOH quickly underwent dehydration to isobutylene (observed and identified by GC-MS). The attempted DODH of 1,2-hexanediol in water showed very little conversion and not even traces of any of the expected products. For comparison, Shiramizu and Toste[5] tested the efficiency of various alcohols for the CH_3ReO_3-catalyzed DODH of 1,4-anhydroerythritol to 2,5-dihydrofuran and observed that while 1-butanol was a much better reductant than 2-butanol (70% vs 0% yield), 3-pentanol was better than 2-pentanol which in turn was better than 1-pentanol (alkene yields of 91%, 78%, and 51%, respectively).

Catalyst Screening and Characterization. Having established that ^{i}PrOH was the most efficient reductant, other molybdenum-based catalysts were tested (Table 3; additional catalysts are shown in Table S2). Gratifyingly, the cheapest catalyst, AHM, was the most efficient—the only coordination compound with a comparable efficiency was

Table 3. Comparison of Molybdenum-Based Catalysts in the DODH of 1,2-Decanediol in ^{i}PrOH[a]

catalyst	yields [%] of			
	C=C	C=O	2°OH	1°OH
AHM	49	10	5	15
$MoO_2Me_2(bipy)$[b]	46	11	3	12
$(Bu_4N)_2Mo_6O_{19}$	42	8	9	23
AHM + Bu_4NOH[c]	55	~0	22	3
AHM + AcOH[d]	37	8	3	11
recycled catalyst 1[e]	38	10	4	18
recycled catalyst 2[f]	20	4	2	10

[a] Reaction conditions A were employed (see Experimental Section); additional catalysts are shown in Table S2 in the Supporting Information. Unless otherwise noted, the conversion of the diol was >98%. [b] bipy = 2,2′-bipyridine; 89% conversion. [c] Six milliliters of a 1 M solution of Bu_4NOH in MeOH was added. [d] Acetic acid (1.2 equiv with respect to 1,2-decanediol) was added to the reaction mixture; 92% conversion. [e] The black precipitate obtained from the AHM-catalyzed DODH of 1,2-hexanediol; the alkene yield includes 1-decene (24%) and isomers of decene and decane (14%). [f] The black precipitate obtained by heating AHM in ^{i}PrOH in the absence of a diol; 58% conversion.

$MoO_2(CH_3)_2(bipy)$ which, although not very difficult to prepare,[35−37] is much more expensive. Among the tested polyoxomolybdates, the compound $(Bu_4N)_2Mo_6O_{19}$[38] resulted in an alkene yield almost as high as that for AHM (42% vs 49%), a slightly higher yield of reduced species (74% vs 69%), and very little catalyst precipitation at the end of the experiment. The addition of a weak acid, 1.2 equiv of acetic acid (in order to mimic the acidity of sugar acids like mucic acid[6,39]), resulted in a lower yield, but the product distribution was unaffected. The addition of a strong base (15 mol % of Bu_4NOH),[40] on the other hand, not only improved the alkene yield but also changed the product distribution; this will be discussed in more detail below. Since strongly acidic conditions ultimately result in the precipitation of MoO_3, acids stronger than acetic acid were not added.

Upon completion of an experiment, a black powder could typically be isolated by filtration; in order to characterize it and test its recyclability or regeneration, a large amount was intentionally prepared by conducting a regular DODH of 5 g of 1,2-hexanediol in 100 mL of ^{i}PrOH under hydrogen using 1.23 g of AHM; after 12 h, 1.1 g of black precipitate (elemental analysis: 13.0% C, 2.4% H, 1.8% N, and 55.7% Mo) was isolated. As evidenced by X-ray powder diffraction, the powder was amorphous; its infrared spectrum is shown in Figure S2. Due to mechanical loss during the isolation, it cannot be unequivocally concluded that all of the molybdenum precipitates at the end of the reaction, but at least 90% could be recovered, and it was demonstrated that AHM could be regenerated from the precipitate: Pyrolysis at 500 °C for 5 h resulted in a gray-blue powder ($MoO_{<3}$) that by dissolution in aqueous ammonia followed by slow evaporation of the solvent was converted to AHM (identified by X-ray powder diffraction).

Based on the relatively high carbon content of the powder, it was tentatively assumed to contain a polyoxomolybdate and at least one coordinated diolate ion, although it cannot be excluded that it is a mixture of compounds. The presence of a diolate ion in the formula was supported by the preparation of a similar black precipitate by heating 2.43 g of AHM in 100 mL of ^{i}PrOH to 240−250 °C with no diol present; after 12 h, 1.8 g of black precipitate containing less carbon (elemental analysis: 1.8% C, 1.2% H, 2.8% N, 64.3% Mo) and with a markedly different infrared spectrum (Figure S2) was isolated. The catalytic activities of the two black precipitates were tested; although both were less efficient than AHM, the black powder that had been precipitated in the presence of a diol resulted in a total yield of reduced species of 60%. Notwithstanding the benefits of being able to recycle a pseudoheterogeneous catalyst (AHM is insoluble in ^{i}PrOH at room temperature) without the need for regeneration, the low cost of AHM in combination with its trivial regeneration makes the direct recycling less important, and repeated use of the black precipitate was therefore not attempted.

Side Reactions and Byproducts. In addition to the desired DODH reaction, two molybdenum-catalyzed side reactions took place, namely dehydration of the diol and transfer hydrogenation of the hereby-formed aldehyde and ketone. Thus, the DODH of 1,2-decanediol always resulted in the formation of 2-decanone, 2-decanol, and 1-decanol, which were routinely quantified; although decanal was never observed, the two acetals formed by condensation of decanal and 1,2-decanediol were observed, when the reaction was stopped before completion (see Supporting Information). Although the dehydration of diols was not the desired reaction, the rhenium- and molybdenum-catalyzed dehydration of alcohols to alkenes has been investigated, in particular by Klein Gebbink and co-workers.[4,41−44] The viability of the proposed pathway was confirmed by adding 15 mmol of either 2-decanone or decanal to the AHM-catalyzed DODH of 1,2-hexanediol in ^{i}PrOH under reaction conditions A (see Experimental Section). Fifty-four percent of the ketone remained unconverted, and the yield of 2-decanol was 39%; neither 1-decanol nor 1-decene was observed. The conversion of the aldehyde was complete, but the yield of 1-decanol was only 46%; the remaining products were not immediately identified, but the aldehyde is likely to form acetals or undergo aldol condensation. The product distribution from these experiments is in agreement with the composition of the reaction mixtures in ^{i}PrOH (10% **C═O**, 5% **2°OH**, 15% **1°OH**), where no decanal was ever observed, and the absence of 1-decene in both experiments excludes the possibility that the alkene is formed through a sequential dehydration−reduction−dehydration of the diol.

Three other minor byproducts were 1-isopropoxy-2-decanol (see Supporting Information for characterization; estimated GC yield 5−10%), diisopropyl ether, and propylene; the quantification of propylene will be discussed below.

Reactivity of Various C_6 Diols. The characteristic group of the model compound 1,2-decanediol, that is, a vicinal diol with a primary and a secondary OH group, is a common motif in glycerol, sorbitol, and open-chain sugars, but it does not necessarily describe the reactivity of vicinal diols containing two secondary OH groups adequately, and the AHM-catalyzed DODH of 3,4-hexanediol and *cis*- and *trans*-1,2-cyclohexanediol in ^{i}PrOH was therefore investigated. These results are summarized in Table 4, whereas the results for the DODH of diols containing one or two tertiary alcohol groups are compiled in Table S3. The hexene yields from 1,2-hexanediol—which was included to take the effect of the shorter aliphatic chain into account—and from 3,4-hexanediol were similar to the yield of 1-decene from 1,2-decanediol, but the cyclic diols displayed a markedly different reactivity: The *cis* isomer underwent complete conversion, but only 29% of cyclohexene formed; the major product (42%) was cyclohexanol, while only traces of cyclohexanone were observed, indicating that transfer hydrogenation of cyclohexanone is very efficient. The conversion of the *trans* isomer was incomplete, and the yields of alkene and alcohol were

Table 4. Comparison of the AHM-Catalyzed DODH of C_6 Diols in ^{i}PrOH[a]

	yields [%] of			
substrate	C═C	C═O	2°OH	1°OH
1,2-hexanediol	46	9	traces	16
+ 3 mL of MeOH	49	15	3	11
+ 3 mmol of Bu_4NOH[b]	77	3	5	5
+ 3 mmol of pyridine	42	15	13	15
3,4-hexanediol[c]	42[c]	17	5	
+ 3 mmol of Bu_4NOH[b]	69[c]	16	3	
cis-1,2-cyclohexanediol	29	traces	42	
+ 3 mmol of Bu_4NOH[b]	47	traces	45[e]	
trans-1,2-cyclohexanediol[d]	14	4	24	

[a] Reaction conditions B were employed (see Experimental Section); more substrates are shown in Table S3 in the Supporting Information. Unless otherwise noted, the conversion of the diol was >98%. [b] Three milliliters of 1 M Bu_4NOH in MeOH was added. [c] Mixture of isomers; calculation of 3-hexene yield was complicated by partial overlap with $^iPr_2O$ on the GC. [d] Conversion was incomplete. [e] Yield based on GC-MS due to partial overlap with Bu_3N on the GC.

14% and 24%, respectively. Different reactivities of the *cis* and *trans* isomers have also been observed for rhenium,[5,7,45] but only the *cis* isomer was investigated for vanadium:[27] It displayed low conversion (25%) and an alkene yield of 15%.

The addition of base was even more beneficial for the C_6 diols than for 1,2-decanediol: The addition of 15 mol % of Bu_4NOH (added as a 1 M solution of Bu_4NOH in MeOH) resulted in yields of hexene from the DODH of 1,2-hexanediol and 3,4-hexanediol of 77% and 69%, respectively, while the combined yield of the reduced species cyclohexene and cyclohexanol from the DODH and from the sequential dehydration and reduction of *cis*-1,2-cyclohexanediol was 92%. Even though the addition of only methanol did result in a slightly higher alkene yield and a different selectivity, the major improvement was a result of the base. The addition of 15 mol % of the six bases NaOH, Na_2CO_3, CH_3COONa, LiOMe, Et_3N, and pyridine was not beneficial: The three sodium salts and the lithium salt resulted in 1-hexene yields of 0%, 7%, 2%, and 6%, respectively, and very low conversions; Et_3N resulted in an alkene yield of 32% and incomplete conversion, and pyridine had only a minor effect. The different behavior of NaOH and Bu_4NOH can probably be ascribed to the insolubility of Na_2MoO_4, which displayed no catalytic activity at all. The same is possibly true for Li_2MoO_4, whereas the lower alkene yield upon the addition of Et_3N might be ascribed to coordination of the amine to the molybdenum center.

Deoxygenation of Allylic Alcohols and Benzyl Alcohol.

We had previously[29] observed a Mo-catalyzed reductive homocoupling of benzyl alcohol (BnOH) to bibenzyl, and if this reactivity also applied to allylic alcohols, the main product from the DODH of glycerol might not be allyl alcohol (as would be expected from Scheme 3a) but 1,5-hexadiene, presumably formed by reductive homocoupling of the allyl alcohol formed by DODH of glycerol. The reactivity of BnOH and allylic alcohols was therefore investigated by subjecting them to reaction conditions similar to those of the diols.

First, a mixture of 80 mmol of BnOH and 2.5 mol % of AHM in 100 mL of ^{i}PrOH was heated to 220 °C for 12 h in a pressurized autoclave, which led to the incomplete conversion to 7% of bibenzyl (yield multiplied by 2 to take the stoichiometry into account) and 60% of toluene; the only oxidation product was acetone, which was observed by NMR. The addition of 7.5 mol % of base (1 M Bu_4NOH in MeOH) and prolongation of the heating time to 18 h resulted in a markedly higher toluene yield (93%) and a lower yield of bibenzyl (4%); using EtOH instead of ^{i}PrOH and still adding the base gave similar yields and product distribution (88% and 2%, respectively) as well as the oxidation product acetaldehyde, which was observed as its diethyl acetal by GC-MS. For comparison, the reactivities of (*R*,*R*)-hydrobenzoin and *meso*-hydrobenzoin were tested by heating 10 mmol of one of the isomers and 6 mol % of AHM in 50 mL of ^{i}PrOH to 220 °C for 1000 min in a pressurized cylinder. For both isomers, the major product was toluene (*R*,*R* 31%, *meso* 44%; the yield has been divided by 2 to take the stoichiometry into account), but significant amounts of *trans*-stilbene (*R*,*R* 27%, *meso* 23%) and bibenzyl (*R*,*R* 16%, *meso* 13%) also formed; no benzyl alcohol was detected. The reactivity of 1-phenyl-1,2-ethanediol was tested by heating 20 mmol of 1-phenyl-1,2-ethanediol and 5 mol % of AHM in 50 mL of ^{i}PrOH to 250 °C for 1000 min in a pressurized cylinder. The main product was 2-phenylethanol (estimated yield 20−25%), while styrene, ethylbenzene, toluene, 1-phenylethanol, and acetophenone were all present in estimated yields below 6%.

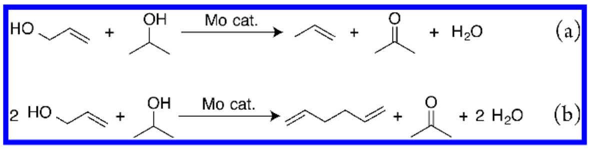
Second, a mixture of 80 mmol of the allylic alcohol 1-hexen-3-ol and 2.5 mol % of AHM in 100 mL of ^{i}PrOH was heated to 220 °C for 12 h, which led to the formation of ∼9% hexene isomers, ∼9% dodecadiene isomers, and acetone as the oxidation product. In addition to ∼25% unconverted 1-hexen-3-ol, 2-hexen-1-ol had formed (the *cis* and *trans* isomers could not be distinguished by GC-MS), thus indicating that AHM catalyzes the 1,3-transposition of allylic alcohols; the molybdenum-catalyzed 1,3-transposition of allylic alcohols has previously been investigated,[46−49] and this reaction can explain the formation of isomers of hexene and dodecadiene. In confirmation, the subjection of *trans*-2-hexen-1-ol to the same conditions resulted in a reaction mixture with an almost identical composition. The addition of 7.5 mol % base (1 M Bu_4NOH in MeOH), prolongation of the heating time to 18 h, and increase of the temperature to 250 °C resulted in a significantly higher hexenes yield (65%); the use of EtOH instead of ^{i}PrOH resulted in a practically identical yield and the formation of acetaldehyde as the oxidation product, while the hexenes yield in MeOH was only 7%.

Third, a mixture of 70 mmol of allyl alcohol, 1.4 mol % of AHM, and 4.2 mol % base (1 M Bu_4NOH in MeOH) in 50 mL of ^{i}PrOH was heated to 250 °C for 18 h, which led to the formation of 8% 1,5-hexadiene and 22% propylene; the conversion was 86%. In EtOH, the yields were 9% and 28%, respectively, while the conversion was 86%. Although a yield of 28% is not high, the absence of other significant byproducts than 1,5-hexadiene as well as the high yields of deoxygenation products from the allylic alcohol 1-hexen-3-ol are promising for the attainment of a higher yield under conditions optimized for the quantification of gases.

The yield of propylene was determined by allowing the gas from a cylinder that had cooled to room temperature to pass through 250 mL of CH_2Cl_2 containing 1.5 mL of bromine and 1 g of PhBr as a reference; the amount of 1,2-dibromopropane was determined by GC. The quantification of propylene was not only complicated by the fact that propylene is a gas that might escape prior to its bromination—which might not be quantitative—but also by the aforementioned formation of propylene by dehydration of ^{i}PrOH. To take the dehydration into account, an AHM-catalyzed DODH of 1,2-hexanediol in ^{i}PrOH using reaction conditions B and adding 15 mol % of Bu_4NOH was conducted, and the amount of propylene formed by dehydration of ^{i}PrOH was quantified (2.2 mmol from 50 mL of ^{i}PrOH); this has been subtracted from the amount of propylene formed by the deoxygenation of allyl alcohol in ^{i}PrOH.

In summary, we find that not only benzyl alcohol but also allylic alcohols undergo two molybdenum-catalyzed reactions, namely a deoxygenation (Scheme 4a) and a reductive homocoupling (Scheme 4b). Formally, both reactions are reductions, and the corresponding oxidation products are acetone, when the solvent/reductant is ^{i}PrOH, and acetaldehyde diethyl acetal, when the solvent/reductant is EtOH.

Scheme 4. Molybdenum-Catalyzed Transformations of Allyl Alcohol: (a) Deoxygenation to Propylene; (b) Reductive Homocoupling to 1,5-Hexadiene



The preparation[50,51] and use[52−55] of 1,5-hexadiene has received some attention, but it is not a commonly employed unsaturated hydrocarbon today; this might, however, change, if the selectivity of the molybdenum-catalyzed deoxygenation can be tuned toward the reductive homocoupling of allyl alcohol instead. The deoxygenation and reductive homocoupling of allylic alcohols are not unprecedented reactions: titanium-mediated[56,57] and lanthanum metal-assisted[58] examples exist, and allyl and benzyl ether have been shown to undergo $TiCl_4$- or $(C_5H_5)TiCl_2$-catalyzed hydrogenolysis by $LiAlH_4$.[59] In addition, propylene—and many other species—form when allyl alcohol reacts with $PdCl_4^{2-}$,[60] and $HCo(CN)_5^{3-}$ catalyzes the deoxygenation of allylic alcohols using hydrogen as the reductant.[61] That said, the molybdenum-catalyzed deoxygenation of allylic alcohols using another alcohol as the reductant has, to the best of our knowledge, not been described before.

DODH of Glycerol and Erythritol. Moving on to a biomass-derived polyol, the AHM-catalyzed DODH of glycerol in ^{i}PrOH was attempted. The amounts of glycerol available from biomass pale in comparison to carbohydrates and their reduced sugar alcohols, but—in contrast to higher polyols like sorbitol—glycerol is stable under the reaction conditions and therefore serves as a reasonable model compound. In addition, large amounts of waste glycerol are inevitably obtained in the production of biodiesel by trans-esterification of triglycerides, and the conversion of this waste product into the more valuable chemical allyl alcohol could benefit the overall economy of a biorefinery.

When glycerol was subjected to reaction conditions B at 250 °C and adding 15 mol % of base (1 M Bu_4NOH in MeOH), the conversion was complete, and in addition to 4% of allyl alcohol and traces of 1,5-hexadiene, 19% of propylene was quantified as 1,2-dibromopropane as described above. In EtOH, the conversion was still complete, and in addition to traces of allyl alcohol and 1,5-hexadiene, 9% of propylene was quantified. It is worth noting that although ^{i}PrOH and EtOH gave similar yields for the AHM-catalyzed deoxygenation of allylic alcohols, ^{i}PrOH was more efficient for the DODH, thus explaining the different yields of propylene from glycerol, which requires a sequential DODH and deoxygenation. As discussed above, a higher yield of propylene might be found under conditions optimized for the quantification of gases.

The DODH of the C_4 sugar alcohol erythritol resulted in the formation of 39% of 2,5-dihydrofuran using reaction conditions B at 250 °C; addition of 15 mol % of base (1 M Bu_4NOH in MeOH) lowered the yield to 27%, which might be explained by a smaller tendency for erythritol to form the proposed intermediate 1,4-anhydroerytrhitol under basic conditions. Isomers of butene were only observed in very small amounts, and no 1,3-butadiene was detected. The DODH of the proposed intermediate 1,4-anhydroerythritol using reaction conditions B yielded 75% of 2,5-dihydrofuran in the absence of base and 74% in the presence.

DFT Calculations. To rationalize the different reactivities of the employed reductants (diol, ^{i}PrOH, and H_2), a density functional theory (DFT) study of the reduction of molybdenum(VI) to molybdenum(IV) was performed as an extension to our previously published results on the mechanism on the molybdenum-catalyzed DODH of diols using the diol itself as the reductant.[30] Using the diol itself or ^{i}PrOH as reductants, the reduction was found to be most favorable when a diolate ion was coordinated to the molybdenum center (i.e., when the diol itself was the reductant, two diolate ions were coordinated to the molybdenum center). Using H_2 as the reductant, the simultaneous addition of hydrogen to both oxide ligands proved most favorable; a mechanism involving the formation of a molybdenum hydride as intermediate as suggested by Mayer and co-workers[62] was also studied. All investigated structures are compiled in Supporting Information.

As seen in Figure 1, the transition state for the reduction with the diol is lower than the one for ^{i}PrOH (by 10.4 kcal/mol), which is in turn lower than the one for H_2 (by 10.3 kcal/mol). These results are in agreement with the observed lack of reduction by hydrogen even at high pressures and also explain the need for higher temperatures when ^{i}PrOH is oxidized instead of the diol (240−250 °C vs 190−200 °C).

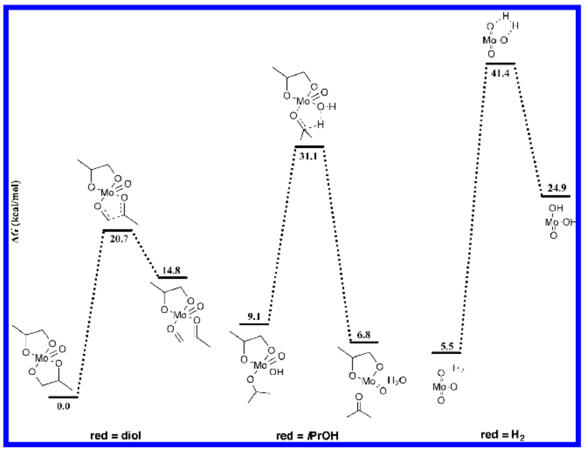


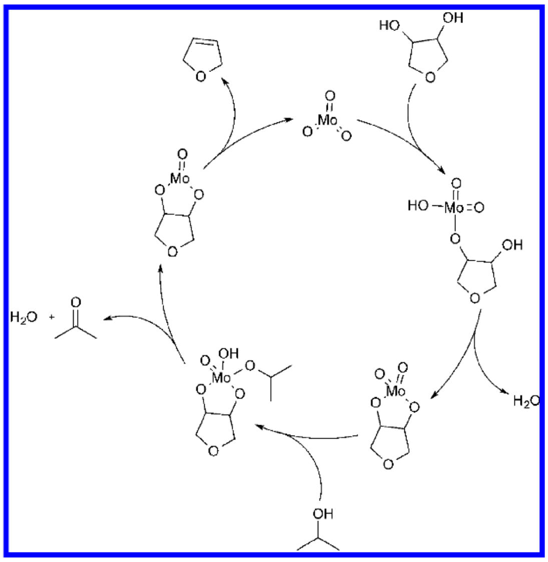
Figure 1. Comparison of the free energies for the reduction of molybdenum(VI) to molybdenum(IV) by 1,2-propanediol, ^{i}PrOH, and H_2.

In analogy with a previously published investigation of the CH_3ReO_3-catalyzed DODH of 1,4-anhydroerythritol driven by the oxidation of 3-octanol,[63] we studied the mechanism of the molybdenum-catalyzed DODH of 1,4-anhydroerythritol driven by the oxidation of ^{i}PrOH. The catalytic cycle is shown in Scheme 5.

The proposed reaction mechanism consists of condensation of MoO_3 with the diol in two steps to form the molybdenum(VI) diolate, followed by coordination and transfer hydrogenation of ^{i}PrOH and finally alkene extrusion to form 2,5-dihydrofuran and MoO_3. The corresponding free-energy diagram is shown in Figure 2. Formation of the diolate complex from MoO_3 and 1,4-anhydroerythritol via **TS1−2** and **TS3−4** is relatively facile since the diol is already in the right conformation to form the five-membered diolate complex. Coordination of ^{i}PrOH to the already crowded diolate complex (**TS5−6**) is more demanding with an activation barrier of 7.1 kcal/mol. The step with the highest activation barrier, however, is the oxidation of ^{i}PrOH (**TS7−8**) with an activation barrier of 24.1 kcal/mol. The last step in the reaction sequence, the extrusion of 2,5-dihydrofuran, has the second-highest activation barrier at 13.8 kcal/mol. An illustration of the transition state for the alkene extrusion (**TS9−10**) is shown in Figure 3, while the transition state for the reduction of ^{i}PrOH (**TS7−8**) is shown in Figure 4.

The DFT calculations carried out in this work reproduced the marked differences between the three fundamentally different types of reductants, namely the diol, ^{i}PrOH, and hydrogen. This agreement with experimental data gives promise that further

Scheme 5. Catalytic Cycle for the DODH of 1,4-Anhydroerythritol Driven by Oxidation of ^{i}PrOH



theoretical studies could aid in the discovery of new and more efficient transition-metal catalyzed DODH processes. Furthermore, the calculated energy profile for the deoxydehydration of erythritol clearly pinpoints the reduction of the metal center prior to extrusion of the alkene as the rate-limiting transition state.

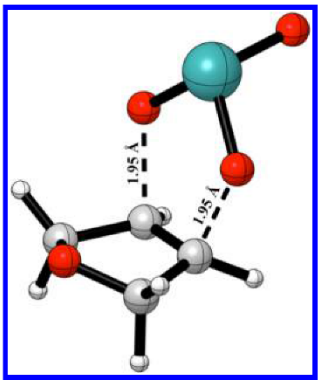


Figure 3. Transition state **TS9−10** for the extrusion of 2,5-dihydrofuran.

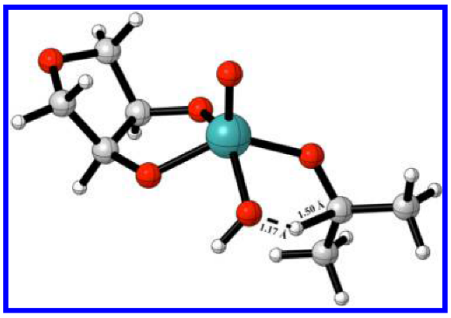


Figure 4. Transition state **TS7−8** for the reduction of ^{i}PrOH.

■ CONCLUSIONS

In summary, a cheaper and more sustainable DODH process for the conversion of vicinal diols into the corresponding alkenes has been developed. The process relies on a molybdenum-based catalyst, in particular the cheap and commercially available $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$ (AHM), and the use of ^{i}PrOH as both a solvent and reductant: Using 5 mol % of catalyst and heating the reaction mixture to 240−250 °C for 12−18 h, alkene yields can

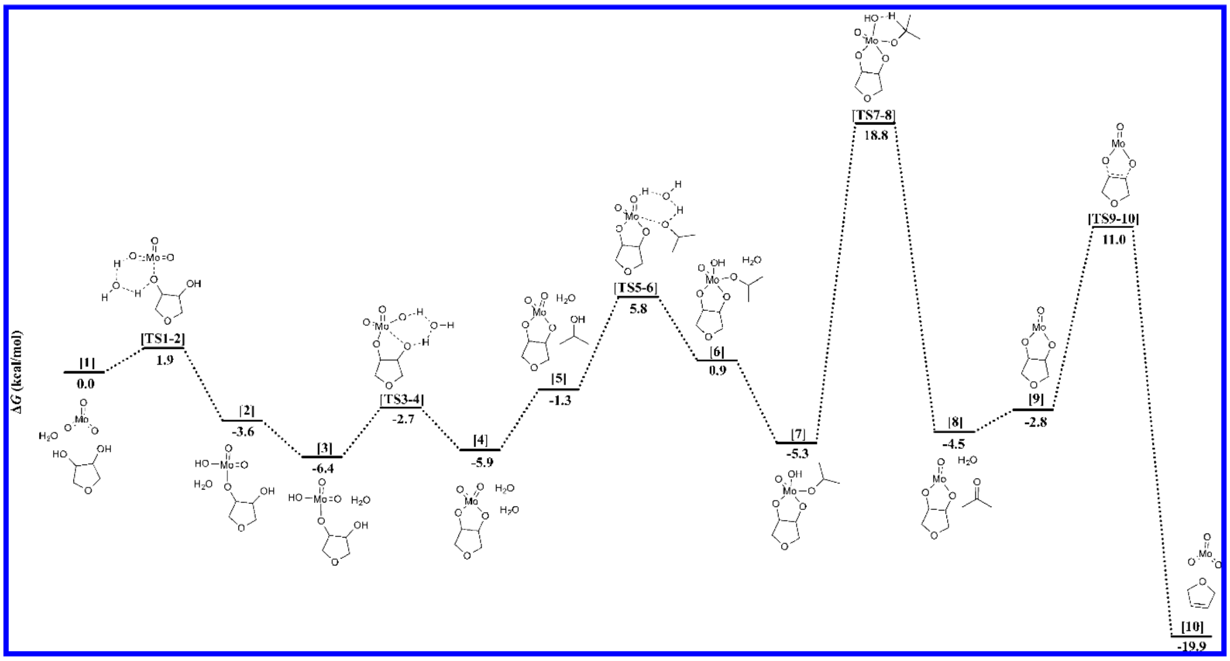


Figure 2. Free-energy diagram for the DODH of 1,4-anhydroerythritol at 298 K.

be as high as 77%, and the combined yield of reduced species can reach 92%. The scope of the reaction has been expanded to glycerol, which undergoes DODH to allyl alcohol followed by deoxygenation to propylene, and to erythritol, which undergoes etherification to 1,4-anhydroerythritol followed by DODH to 2,5-dihydrofuran. The molybdenum-catalyzed deoxygenation of allylic alcohols and benzyl alcohol driven by the oxidation of either ^{i}PrOH or EtOH has been optimized experimentally, and—under basic conditions—the yield can reach 65% for allylic alcohols and 93% for benzyl alcohol.

Neither the cost nor the sustainability of the catalyst, the solvent, and the reductant hamper the implementation of this DODH process on an industrial scale, but the isolation and quantification of propylene from the sequential DODH and deoxygenation of glycerol needs to be vastly optimized to be competitive. In addition, the scope of the reaction needs to be expanded to biomass-derived polyols that are cheaper and more available than erythritol and that lead to products with significantly higher values than propylene and allyl alcohol, for instance, 1,3,5-hexatriene.

■ EXPERIMENTAL SECTION

Materials. Unless otherwise stated, all materials were purchased from Sigma-Aldrich in ≥98% purity and used as received. The molybdenum-based catalysts $MoO_2Cl_2(dmso)_2$,[64] $MoO_2(CH_3)_2(bipy)$,[37] $MoO_2Cl_2(bipy)$,[36] $MoO_2Br_2(bipy)$,[36] $(Bu_4N)_2Mo_6O_{19}$,[38] and $(NH_4)_6MnMo_9O_{32}\cdot 8H_2O$[65] were prepared by literature procedures. The preparation of 3,4-hexanediol is described in the Supporting Information. 2-Ethyl-1,2-butanediol was prepared by a Sharpless dihydroxylation[66] of 2-ethyl-1-butene, which was prepared by the Wittig reaction[67] of 3-pentanone with $Ph_3P{=}CH_2$; 3-ethyl-3,4-hexanediol was prepared by a Sharpless dihydroxylation[66] of 2-ethyl-3-hexene, which was prepared by the Wittig reaction[67] of 3-pentanone with $Ph_3P{=}CHCH_2CH_3$.

Reaction Conditions A. Forty millimoles of diol, 2.0 mmol of catalyst (5 mol %, calculated with respect to the amount of molybdenum), 500 mg of hexadecane (internal standard), and 100 mL of solvent were mixed in a 300 mL PTFE cup and placed in a 400 mL Berghof autoclave with a magnetic stir bar (500 r.p.m.) and computer-controlled heating plate. The autoclave was sealed, pressurized with 10−25 bar of H_2 or N_2, and heated to 250 °C for 800 min; the temperature typically stabilized between 240 and 250 °C, while the maximum pressure was 60−90 bar (a typical heating profile is shown in Figure S1). When the system had cooled to room temperature, the pressure was released, and the reaction mixture was filtered to remove a fine, black precipitate and analyzed by GC (for determination of conversion and yields) and GC-MS (for observation and identification of other products).

Reaction Conditions B. The experimental setup was identical to that in reaction conditions A except for the following changes: The reactions were conducted on half scale in a 150 mL Swagelok cylinder, which for 18 h was placed in an aluminum block that had been preheated to 250 °C. Neither the temperature nor the pressure could be monitored in this experimental setup, but on the other hand, it was possible to conduct up to four parallel experiments.

Computational Methods. Visualization and comparison of structures were performed in Maestro version 9.3.515.[68] DFT calculations were performed in Jaguar[69] with the B3LYP functional[70−72] with added D3 corrections.[73] We used the LACVP** basis set, which applies the Hay−Wadt ECP and basis set for molybdenum, and the 6-31G** basis set for all other atoms.[74] Transition states were found by a quadratic synchronous transit (QST)[75] search. Intermediates were found by minimizing the transition states toward both the expected starting material and the expected final product. All intermediates and transition states were characterized by a full, analytic frequency calculation at 25 °C that resulted in only positive frequencies for intermediates and exactly one imaginary frequency for transition states. Approximate Gibbs free energies in the solution phase (G_{solv}) were obtained by combining the solution phase SCF energies ($E_{SCF,solv}$), which were calculated with the Poisson−Boltzmann solver (PBF)[76,77] using standard parameters for methanol, with the vibrational contribution from the gas phase ($G_{gas} - E_{SCF,gas}$) in line with earlier work ($G_{solv} = E_{solv} + G_{gas} - E_{gas}$).[78] The computational model system was kept neutral to avoid complications when comparing charged and neutral species computationally.[79] We do not rule out the possibility of charged molecular species but rather suggest the neutral complexes treated in this work to be suitable computational models of the actual complexes. The structural figures in the article were created with CYLview[80] using the POV raytracer for rendering.[81] Structural figures in the Supporting Information were made with XYZViewer.[82]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

This file is available free of charge on the ACS Publications website at DOI: 10.1021/acscatal.5b00427.

> Typical heating profile obtained under reaction conditions A; infrared spectra of precipitated catalyst; optimization of reaction conditions; test of additional molybdenum-based catalysts; details on the formation of acetals and characterization of an ether; reactivity of diols containing tertiary OH groups; structures and energies for all the relevant complexes (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by a Sapere Aude research leader grant (P.F.) from the Danish Council for Independent Research, Grant 11-105487.

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Vanadium-Catalyzed Deoxydehydration of Vicinal Diols using Isopropyl Alcohol as Reductant

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Keywords: biomass • deoxydehydration • vanadium • polyols • alkenes • DFT

ABSTRACT

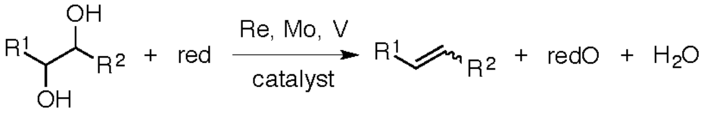
The deoxydehydration (DODH) of diols driven by oxidation of *i*PrOH to acetone catalyzed by the cheap and commercially available catalyst ammonium metavanadate, NH_4VO_3, has been developed. The reaction proceeds at 230 °C in a pressurized autoclave and shows a strong preference for terminal diols: 1,2-Decanediol was converted to 1-decene in 51% yield, whereas 3,4-hexanediol was found to be completely unreactive. The lack of reactivity of internal diols contrasts the analogous rhenium- and molybdenum-catalyzed DODHs, and a theoretical study employing density functional theory (DFT) calculations was therefore warranted. The dramatic difference in reactivity was found to be rooted in the formation of stable—but unreactive—complexes between the internal diols and the vanadium center, which hindered efficient

catalysis. The same reasoning was applicable to ethylene glycol that was found to be unreactive and even capable of inhibiting the reaction of otherwise reactive diols.

INTRODUCTION

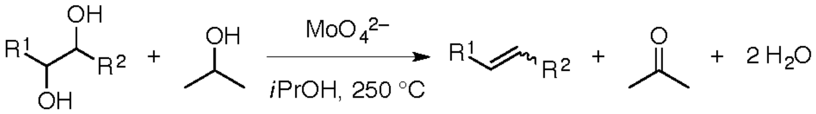
With the political ambitions for substituting large amounts of the fossil fuels used for transportation and energy production with sustainable biomass-based alternatives, it is important to make the production of these as efficient as possible. Since the production of organic platform molecules (e.g., olefins and aromatics) is closely linked to the production of transportation fuels,[1] the overall economy of biorefineries depends on effective utilization of the whole biomass feedstock. One important stream of biomass that is already being processed is triglycerides, which in methanol undergo trans-esterification to give fatty acid methyl esters (FAME) and glycerol; the valorization of the byproduct glycerol would be a proof of concept of the ability of a biorefinery to utilize the entire biomass stream.[2]

The hydroxyl group is a common motif of carbohydrates, which are a major part of all biomass. One strategy for reducing their oxygen content while preserving functionality is the deoxydehydration (DODH) reaction that transforms a vicinal diol into the corresponding alkene in a single reaction step (Scheme 1). The DODH reaction[3,4,5] is driven by the oxidation of a sacrificial reductant and has typically been catalyzed by various rhenium-based compounds; although this approach is still being investigated by several groups,[6,7,8] the recently developed molybdenum[9]- and vanadium[10,11]-catalyzed DODH reactions could be relevant due to the significantly lower prices of the elements. In addition to a substitution of the scarce element rhenium,[12] the use of the DODH reaction on industrial scale requires a substitution of the expensive reductant (e.g., PPh_3 or 3-octanol) and the toxic or biomass-immiscible solvents (e.g., benzene, chlorobenzene, or 3-pentanol) normally used.



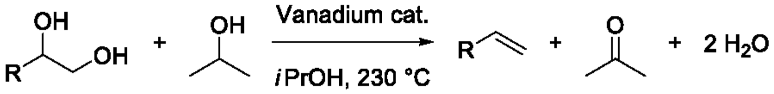
Scheme 1. Generalized Re-, Mo-, or V-Catalyzed DODH of a Vicinal diol into an Alkene, Driven by the Oxidation of a sacrificial Reductant (“red”).

We have recently demonstrated the use of the cheap and commercially available $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$ as catalyst for the DODH of vicinal diols in *i*PrOH, which serves as both the solvent and the reductant (Scheme 2).[9] The alkene yield could be as high as 77% and the major byproducts were the carbonyl compounds formed by dehydration of the diol and the alcohols formed by transfer hydrogenation of these carbonyl compounds; the total yield of reduced species could be as high as 92%.



Scheme 2. Molybdate-Catalyzed DODH of a Vicinal diol into an Alkene, Driven by the Oxidation of *i*PrOH to Acetone.

In the present work, we show that a wide variety of commercially available vanadium-based compounds efficiently catalyze the DODH of vicinal diols. At the onset our main objective was to investigate the possibility of using an alcohol as both the solvent and reductant (Scheme 3). In the following sections we deliberate on a range of solvents, reductants, substrates, and ligands that we have tested. During our investigation a specific difference in selectivity for the V-catalyzed DODH was observed, which warranted an in-depth computational study employing DFT calculations.



Scheme 3. Vanadium-Catalyzed DODH of a Vicinal 1,2-diol into a Terminal alkene, Driven by the Oxidation of *i*PrOH to Acetone.

RESULTS AND DISCUSSION

Initial Optimizations. The starting point for this study was inspired by the reaction conditions used for Mo-catalyzed DODH.[9] The experiments were performed either in an autoclave or in a Swagelok cylinder, and in a standard experiment with *i*PrOH as the solvent, the maximum pressure would typically be 50–70 bar. For vanadium, a catalyst concentration of 5 mol% was employed and the reaction was found to start when the temperature reached 230 °C and result in full conversion of the most reactive substrates within 17 hours (see experimental section for additional details).

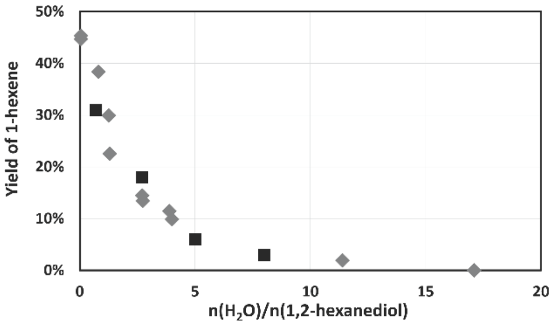


Figure 1. dependence of the yield of 1-hexene from the DODH of 1,2-hexanediol (Reaction Conditions B) on the amount of added water. *Diamonds*: NH_4VO_3 as catalyst. *Squares*: $(NH_4)_6Mo_7O_{24}\cdot4H_2O$ as catalyst.

Water is an inherent byproduct in DODH and an investigation of how it affects the reaction was therefore warranted. A series of reactions, in which water was added in different amounts from the onset of the reaction clearly showed that DODH is hampered already at 2 equiv of water-to-substrate. Interestingly, the sensitivity towards water appears to be very similar for the catalyst based on vanadium (NH_4VO_3), and that based on molybdenum ($(NH_4)_6Mo_7O_{24}\cdot4H_2O$) (Figure 1). An array of known ways to remove water was considered, but molecular sieves were found unable to bind water at this high temperature. Using IR spectroscopy, the areas corresponding to the bending mode of water at 1645 cm^{-1}, was compared at rt between a spectrum of wet *i*PrOH (2 wt% water) and a spectrum after drying of the solvent with 3 Å molecular sieves. The dried solvent and the sieves were heated up in the autoclave to 230 °C and a sample was extracted and filtered, before a new spectrum was recorded at rt. The three spectra clearly showed that the molecular sieves could not retain the water at this high temperature. Chemical reagents, known to react with water, were also tested as water scavengers. These included 2,2-dimethoxypropane and 1,1-dimethoxycyclohexane in amounts of 0.75 and 2 equiv relative to the diol but in any case the addition only resulted in lower yields of alkene at full conversion. Triethyl orthoformate was found to reduce the 1,2-decanediol to 1-decene in a non-catalytic reaction, as already described in literature.[13] Addition of quicklime (CaO) to the experiment resulted in extensive precipitation of a grey powder and no formation of alkene. While these studies did not lead to an improved DODH reaction it is interesting that the dependence of water is so similar for the two different metals, thus leading one to speculate that a suitable method for water separation could be effective for both molybdenum and vanadium-based systems.

Solvent and Reductant. The best choices of reductant in terms of price, sustainability, and atom economy are hydrogen and carbon monoxide, which were tested as reductants and found to yield practically identical product distributions and yields as the reactions that were carried out using the inert N_2 gas (Table 1). The experiments in *i*PrOH were done, because a polar solvent capable of dissolving the biomass is preferred, while the experiments in hexane should clarify whether the applied reductants could be effective at all. The alkene that is formed in hexane, under inert N_2 gas, possibly stems from oxidation of the diol itself as shown previously for molybdenum[14] although in this case no oxidation products were observed; 2-decanone was the only pronounced by-product showing up in the GC spectrum in this experiment. Oxidation of the substrate itself will lower the theoretical yield of reduced species to 50%. Nicholas and Gopaladasu[11] recently showed that CO gas is an effective reductant in DODH catalyzed by $[Bu_4N](salhyd)VO_2$ (salhyd = salicylaldehyde hydrazide) in benzene or chlorobenzene at 160 - 180 °C for 1 to 4 days.

Table 1. Test of H_2 and CO as Reductants in the DODH of 1,2-Decanediol using NH_4VO_3 as Catalyst under Reaction Conditions A.[a]

Gas	Solvent	Conv. [%]	Yields [%] of			
			C=C	C=O	2°OH	1°OH
H_2	hexane	Full	32	6	1	1
N_2	hexane	Full	30	9	3	3
H_2	*i*PrOH	93	48	2	2	6
N_2	*i*PrOH	97	51	2	1	8
CO [b]	*i*PrOH	full	51	2	1	5

[a] Products: 1-decene (C=C), 2-decanone (C=O), 2-decanol (2°OH) and 1-decanol (1°OH). [b] The pressure of CO was 14 bar.

When NH_4VO_3 is used, neither H_2 nor CO gas can act as reductants for the DODH in *i*PrOH. For this reason, it was decided to investigate the alcohol-driven DODH, in which an alcohol is oxidized to form a ketone or an aldehyde. Afterwards, the reductant may be recycled by hydrogenation of the formed carbonyl compound. It is an advantage if the alcohol is cheap, green and capable of dissolving the highly oxygenized compounds usually obtained from biomass, if the system is to become industrially feasible. Results when using a range of different solvents for DODH of 1,2-decanediol is reported in **Table 2**. Starting from methanol and moving to longer primary alcohols give higher yields of 1-decene. Even better outcomes are obtained when secondary alcohols are used, such as isopropyl alcohol (51% yield) or 3-pentanol (46% yield).

Table 2. Comparison of Organic solvents in the NH_4VO_3-Catalyzed DODH of 1,2-Decanediol.[a]

Solvent	Conv. [%]	Yields [%] of			
		C=C	C=O	2°OH	1°OH
MeOH	35	6	1	1	1
EtOH	64	17	4	1	3
*n*PrOH	78	27	2	1	3

*i*PrOH	97	51	2	1	8
3-pentanol	97	46	2	1	6
hexane	full	30	9	3	3
2,2,2-trifluoroethanol [b]	67	19	0	0	3
hexafluoroisopropyl alcohol [b]	61	13	0	0	4
2,4-dimethyl-3-pentanol [c]	full	45	10	0	7
cyclohexanol	98	43	2	2	5

[a] Unless otherwise noted, Reaction Conditions A were employed; Products: 1-decene (C=C), 2-decanone (C=O), 2-decanol (2°OH) and 1-decanol (1°OH). [b] Reaction Conditions B; the substrate was 1,2-hexanediol and 1-heptanol was used as an internal reference. [c] Reaction Conditions B; the substrate was 1,2-hexanediol.

When hexane was used as the solvent, 30% of the desired alkene was still obtained, probably due to oxidation of the diol itself. Therefore, to avoid unwanted oxidation of the substrate, it is important that the sacrificial alcohol is a better reductant than the diol. The fluorinated alcohols was tested to see if the electron-withdrawing fluorine atoms could facilitate higher alkene yields, but that was not the case. Then 2,4-dimethyl-3-pentanol was tested, as it has already proven successful in rhenium-catalyzed DODH of glycerol[15] and phenylethanediol.[16] An alkene yield of 45% was found, which is in line with previously reported results on vanadium-catalyzed DODH in benzene with 2,4-dimethyl-3-pentanol as reductant.[10] Benzyl alcohol was added as a potential reducing agent, but this compound underwent transfer hydrodeoxygenation (HDO) to toluene in about 30 - 40% yield, regardless of whether the solvent was isopropyl alcohol or ethanol. The reaction is an analogue to the recently investigated Mo-catalyzed transfer HDO of benzyl alcohol.[17] Cyclohexanol was also tested, but only 43% of 1-decene was obtained. The conclusion is that isopropyl alcohol remains the best choice for a system aiming to offer the cheapest possible DODH reactivity and with good recyclability of the reductant.

Catalyst Screening. Under these harsh reaction conditions, the vanadium center will presumably exchange most ligands rapidly. Focus was therefore on commercially available vanadium compounds in different oxidation states, rather than of development of complex ligand systems. The results show almost identical yields (50%) for all types and oxidation states of the catalysts (**Table 3**). Even the $(Bu_4N)(dipic)VO_2$ catalyst, that has otherwise proven to be outstanding for DODH carried out in benzene with PPh_3 as the reductant,[10] gave 47% alkene yield when isopropyl alcohol was used.

Table 3. Comparison of Different Vanadium Catalysts for DODH of 1,2-Decanediol.[a]

Catalyst	Conv. [%]	Yields [%] of			
		C=C	C=O	2°OH	1°OH
NH_4VO_3	97	51	2	1	8
Bu_4NVO_3 + dipic [b]	90	45	2	1	7
$(Bu_4N)(dipic)VO_2$ [c]	95	47	2	1	7
V_2O_5	93	47	2	1	8
$VO(isopropoxide)_3$	92	48	2	1	8
$VO(acac)_2$	full	54	4	2	10
$V(acac)_3$	94	50	2	1	7
NH_4VO_3 + acid [d]	93	50	2	1	7
NH_4VO_3 + base [e]	87	40	2	1	5
$(Bu_4N)_3[V_{10}O_{28}H_3]$ + base [f]	91	50	3	0	5
$VOSO_4 \cdot xH_2O$	77	2	1	9	7
Na_3VO_4	37	1	1	0	1
VO(tpp) [g]	84	18	5	0	16

$(Bu_4N)_3[V_{10}O_{28}H_3]$ [h]	92	23	6	0	19

[a] Unless otherwise noted, Reaction Conditions A were employed. Products: 1-decene (C=C), 2-decanone (C=O), 2-decanol (2°OH) and 1-decanol (1°OH). [b] 1.1 equiv of dipicolinic acid to catalyst. [c] 4.5 mol% catalyst. [d] 1.2 equiv of acetic acid to catalyst. [e] 3 equiv of Bu_4NOH to catalyst. [f] Reaction Conditions B; 3 equiv of Bu_4NOH to catalyst was used and the substrate was 1,2-hexanediol. [g] Reaction Conditions B; 1,2-hexanediol used as substrate; 4 mol% of catalyst was used and the reaction time was 990 min; tpp = 5,10,15,20-Tetraphenylporphyrine. [h] Reaction Conditions B; 1,2-hexanediol used as substrate; the reaction time was 1260 min.

The 5,10,15,20-Tetraphenyl-21H,23H-porphyrine vanadium(IV) oxide, VO(tpp), complex was also tested, as it may actually stay coordinated at the reaction temperature. The anticipation was that the bulky ligand could result in higher yields or at least a change in the product distribution. The latter of the two was found with an increase in the yield of the primary alcohol (16%), accompanied by a decrease in the corresponding alkene (18%).

A low yield (23%) was observed when the tetrabutylammonium polymetalate $(Bu_4N)_3[V_{10}O_{28}H_3]$ was used as catalyst. The polymetalate complex only reluctantly gives rise to the DODH-active monomeric vanadium-oxo species; however, this can be favored by addition of tetrabutylammonium hydroxide resulting in 50% alkene yield. The tendency was also found for Mo-catalyzed DODH where the molybdenum complex $(NH_4)_6Mo_7O_{24}\cdot4H_2O$ in conjunction with base, increases the yield of 1-hexene from 46% to 77%.[9] We suggest that the base break up the polymetalate and thereby increases the solubility and reactivity of the catalyst. As expected, addition of tetrabutylammonium hydroxide to the monomeric NH_4VO_3 has a negative effect on the yield. Finally, $VOSO_4\cdot xH_2O$ and Na_3VO_4 resulted in almost no DODH which we ascribe to the low solubility of these complexes.

The highest alkene yield was obtained with $VO(acac)_2$ as catalyst, to give 54% alkene yield and a total of 66% reduced species. This suggests that the catalytic cycle is at least to some extent driven by oxidation of isopropyl alcohol to acetone and not merely by oxidation of the diol itself.

The most pronounced side product is the primary alcohol (1°OH, 1-decanol), followed by a small amount of the ketone obtained by oxidation of the secondary alcohol (C=O, 2-decanone). The secondary alcohol (2°OH, 2-decanol) was only found in some experiments and always in very small amounts. Besides these compounds, we usually observed the isopropyl ether of the diol substrate as previously reported for Mo-catalyzed DODH.[9] However, the 1-isopropoxy-2-hexanol proved to be an end byproduct completely unsusceptible to further reaction. The rest of the substrate is probably lost through polymerization reactions of oxidized diol species, to compounds that are too heavy for GC and GC-MS detection.

Verification of the Experimental Procedure. The same amounts of products were observed when the reactions were carried out in the Swagelok cylinders (Reaction Conditions B) rather than in the autoclave (Reaction Conditions A). The cylinders were firmly sealed and test experiments performed to ensure that they were not leaking out the sample: After DODH of 1,2-decanediol in *i*PrOH, more than 98% of the initial sample weight could be recovered.

Ligands with the Diol Functionality. In order to test the influence of other possible ligands that might be stable under the reaction conditions, small amounts (1.5 equiv relative to vanadium) of an unreactive additive with the diol structure was added (**Table 4**). The electron-poor tetrafluorocatechol was found to strongly inhibit the DODH, and it is therefore expected to stay coordinated to the vanadium center. Those additives that showed a strong influence on the outcome were further tested with a smaller additive-to-vanadium ratio. The biggest change in product distribution was found for 2,3-dihydroxynaphthalene, which yielded an increased amount of 1-hexanol. Addition of the nitrogen analogues of the tested naphthalene-based additives, had little to no effect on the DODH thus implying that only oxygen-based ligands are capable of binding to vanadium and affecting the product distribution.

Table 4. Test of Different Additives to NH_4VO_3-Catalyzed DODH of 1,2-Hexanediol.[a]

Additive	Color of solution	Conv. [%]	Yields [%] of		
			C=C	C=O	1°OH
Ethylene Glycol[b]	Yellow	97	48	3	6
Ethylene Glycol[c]	Yellow	62	32	2	4
Pyrocatechol	Black	64	24	3	15
Pyrogallol	Green	9	5	0	3
3-Fluorocatechol[d]	Brown	31	11	0	8
Tetrafluorocatechol	Brown	0	5	0	0
2,3-Dihydroxynaphthalene	Black	88	15	3	31
2,3-Naphthalenediamine	Yellow	95	50	4	6
1,8-Dihydroxynaphthalene	Black	45	19	2	6
1,8-Naphthalenediamine	Red	91	47	2	5

[a] Unless otherwise noted, Reaction Conditions B were employed and 1.5 equiv of additive to vanadium were assed. Products: 1-hexene (C=C), 2-hexanone (C=O) and 1-hexanol (1°OH). [b] 1 equiv to vanadium. [c] 8 equiv to vanadium [d] 2 equiv to vanadium.

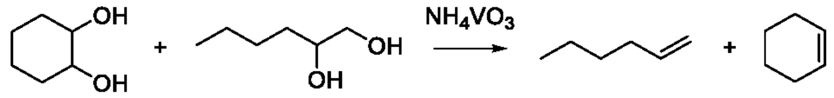
Substrate Scope. The first substrates that were investigated were 1,2-hexanediol and 1,2-decanediol, which both gave roughly 50% alkene yield at full conversion (**Table 5**). Then, a dramatic reduction in yield was observed when employing substrates containing only secondary hydroxyl groups. In the case of the cyclic *trans*- and *cis*-1,2-cyclohexanediol, low conversion and almost no DODH products (5% for *trans* and 1% for *cis*) were observed. In the molybdenum-catalyzed DODH, it was possible to convert 29% of *cis*-1,2-cyclohexanediol into the alkene and 14% of the *trans* stereoisomer.[9] These substrates have also been thoroughly investigated with rhenium and there seems to be a general trend for the DODH reaction to prefer the *cis* stereoisomer.[16,18] This preference is in line with the proposed reaction mechanisms for V,[19] Mo,[9] and Re[20] via a diolate complex in which both of the hydroxyl groups coordinate to the metal center simultaneously. This coordination may be obstructed by the different orientation of the hydroxyl groups in the *trans* stereoisomer. For vanadium, however, low conversion for both *cis* and *trans* isomers were observed.

Table 5 Comparison of Different Substrates in NH_4VO_3-Catalyzed DODH.[a]

Substrate	Conv. [%]	Yield [%] of C=C
1,2-Hexanediol	86, 94	41, 48
1,2-Decanediol	95, 100	51, 50
trans-1,2-Cyclohexanediol[b]	18, 14	5, 5
cis-1,2-Cyclohexanediol[b]	4, 3	1, 1
cis-1,2-Cyclooctanediol	23, 35	3, 5
2-Ethyl-1,2-butanediol	Full	9, 10
(*R*,*R*)-Hydrobenzoin	Full	16 (*trans*)
meso-Hydrobenzoin	Full	30 (*trans*)
rac-1-Phenyl-1,2-propanediol	Full	3/37 (*cis*/*trans*)
1,4-Anhydroerythritol	9	10
1,4-Anhydrothreitol	0	0

[a] Reaction Conditions B were employed; some of the experiments were conducted twice to check the reproducibility of the results. [b] Reaction time was 990 min.

The importance of the orientation of the hydroxyl groups was also observed when 1,2-hexanediol underwent DODH in the presence of either *cis*- or *trans*-1,2-cyclohexanediol (Scheme 4). If the *cis* isomer was added to the reaction, the yield of 1-hexene was dramatically lowered, whereas the *trans* version had a much smaller effect on the deoxydehydration. The most likely explanation for this behavior is that *trans*-1,2-cyclohexanediol is unable to form a vanadium diolate complex, while the *cis* isomer can function as a ligand under the reaction conditions and thus impede the DODH.



cis-1,2-hexanediol	19%	3%
trans-1,2-hexanediol	43%	4%

Scheme 4. The influence by differently oriented hydroxyl groups.

The more flexible *cis*-1,2-cyclooctanediol was tested, to investigate if the steric effects of the cyclic diols, could be of importance. Although the conversion was higher than for the six-membered ring systems, the alkene yield was still very small. There was no alkene formation from the rigid *cis*-norbornylene glycol, nor from the straight-chain 3,4-hexanediol.

Encouraged to discover how selective the vanadium catalyst is towards substrates with at least one primary hydroxyl group, it was decided to move on to more reactive diols. With 2-ethyl-1,2-butanediol, only 10% of the corresponding alkene was detected, due to an unexpected deoxygenation of the tertiary alcohol group. About 50% of 2-ethyl-1-butanol was detected in this experiment. Both diastereoisomers (*meso* and *R*,*R*) of hydrobenzoin was also tested, as the stilbene products will be stabilized by conjugation. In this case, the *trans* isomer of stilbene was almost selectively obtained for both (*R*,*R*) and *meso*-hydrobenzoin (16% and 30% respectively). The could be du to thermal isomerization between *cis*- and *trans* isomers of stilbene or through a selectivity in the reaction pathway. The less reactive 1-phenyl-1,2-propanediol also resulted in a majority of *trans*-β-methylstyrene (37%).

The substrates tested so far have mostly been model compounds of chemicals derived from biomass. Glycerol, on the other hand, is a chemical that is produced in increasing amounts from the production of biodiesel and it is therefore an interesting target molecule for DODH. Our initial experiments on glycerol showed almost no conversion and no formation of allyl alcohol. Small amounts of propylene were detected in the headspace of the cylinders by leading the gas through a solution of Br_2, in CH_2Cl_2, followed by GC detection of the brominated alkene (1,2-dibromopropane). The amounts were not quantified, as the Swagelok cylinders are likely to leak out some of the propylene during the experiment. The same experiment was performed with 1,2-propanediol and ethylene glycol. Almost no alkene was detected in the headspace when using ethylene glycol, while much more 1,2-dibromopropane was observed when using the C_3-diol. The ether analog of glycerol, 3-isopropoxy-1,2-propanediol, did react to form the corresponding alkene from DODH in a decent yield of 46% at 86% conversion.

THEORETICAL CALCULATIONS

In an attempt to gain a deeper understanding of the mechanism of the vanadium-catalyzed DODH reaction and an understanding of the observed reactivity as a function of substitutions on the diol, a theoretical study of the reaction was carried out using DFT, in line with earlier studies.[3,9,21] In the calculations, we used the B3LYP-D3 functional and the LACVP** basis set. In line with earlier work on Re and Mo, the vanadium catalysts were treated as the neutral complex VO_2OH in order to simplify the model as well as being neutral analogue to ammonium metavanadate, the most commercially interesting catalyst used in this study. For the diol, we used 1,2-propanediol as a model compound, the smallest possible diol containing both a primary and secondary alcohol, and a close analogue to 1,2-hexandiol and 1,2-decandiol. All vanadium(V) complexes were considered as singlets (multiplicity of 1), where V(III) complexes were considered in both their singlet and triplet states (multiplicity of 1 and 3, respectively). All transition states and intermediates with a multiplicity of 3 have been marked with an asterisk (*).

We propose the catalytic cycle to consist of the formation of a V(III) diolate followed by an extrusion step in line with the analogous extrusion from Re(V)[20,22] and Mo(VI) complexes.[9,21] The formation of the V(III) diolate is expected to follow one of two pathways: either the formation of a vanadium(V) diolate with the diol followed by a reduction with isopropyl alcohol (Pathway A), or a direct reduction of the vanadate catalyst to a free V(III) moiety with subsequent condensation to the target diolate (Pathway B). These pathways and the extrusion step are sketched in Figure 2.

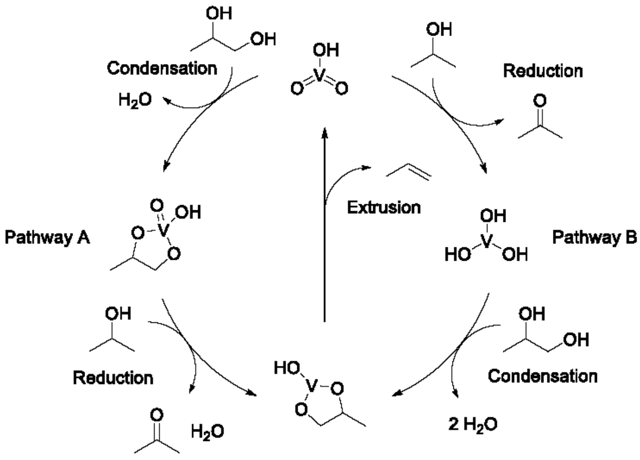


Figure 2: the two overall pathways considered for the vanadium catalyzed DODH reaction.

A previous study has shown favorable energies for a pathway similar to B for the vanadium complex with the dipicolinate (dipic) ligand and PPh_3 as reductant,[19] a method applied by Nicholas and coworkers.[10] In this project however, the goal is to understand the reactivity of the free vanadate catalyst in reactions where isopropyl alcohol, a much cheaper and easily recyclable alcohol, is used as the reductant. Studies have shown an analogue to Pathway B being favorable for rhenium,[20] whereas another study on a molybdenum analogue demonstrated preference for Pathway A.[9] Both studies proved the reduction to be the rate-determining step.

The Reduction Step and Diolate Condensation. The condensation and reduction steps for Pathways A and B were modeled, examining all possible pathways (only intermediates of lowest energies are discussed here – see ESI for all the others). The lowest energy mechanisms to the V(III) diolate **[5]** are shown in Figure 3 (the change in energy from **[A5]** and **[B5]** to **[5]/[5]*** is due to loss of micro solvation effect).

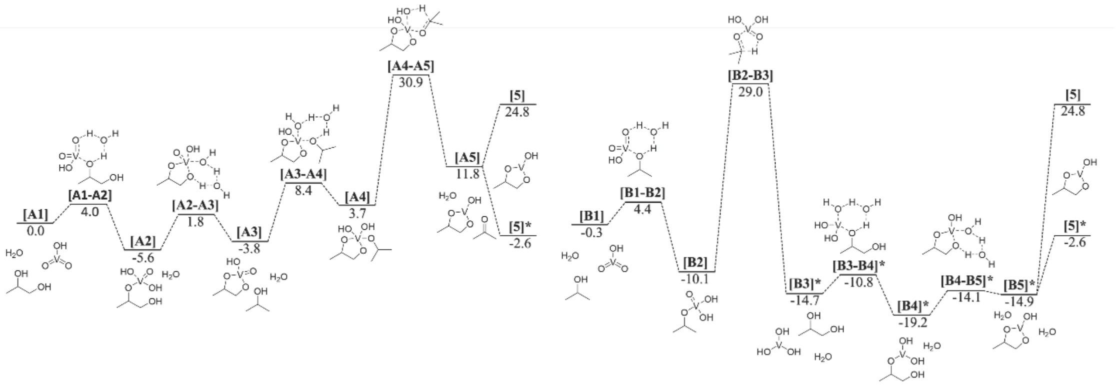


Figure 3. energy diagrams for the lowest energy mechanisms of Pathway A (left) and Pathway B (right).

All vanadium(III) complexes proved more stable in the triplet state. Though high stability of the triplet state is observed, we also show the singlet state, **[5]**, due to the importance of its geometry for further calculations. Calculations showed small energy barriers for the condensation steps as expected, with favorable energies for initial condensation to the secondary alcohol of the diol in both pathways (**[A1-A2]** and **[B3-B4]***). Calculations proved the two mechanisms to have very similar energies with a slight selectivity towards Pathway B with **[B2-B3]** being 1.9 kcal/mol lower in energy than **[A4-A5]**. The geometries of the two transition states are depicted in Figure 4.

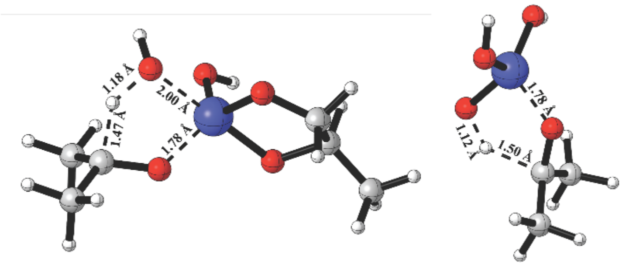


Figure 4. transition state geometries of **[A4-A5]** (left) and **[B2-B3]** (right).

The Extrusion Step. Following the formation of the V(III) diolate, we suspected the reaction to go through a [2+3] extrusion as previously observed with both molybdenum[3,9,21] and rhenium.[20,22] Calculations however, showed a high energy barrier of 48.6 kcal/mol when compared to the vanadate starting point. Therefore, we examined the possibility of a rearrangement mechanism to a 4-membered oxetane capable of [2+2] extrusion, as seen in Figure 5 with the corresponding energy diagram sketched in Figure 6.

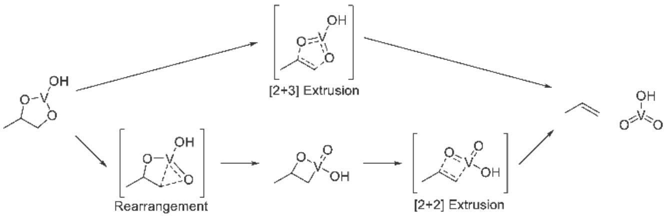


Figure 5. alternative rearrangement mechanism to the classic [2+3]-extrusion step

The energies of the [2+3] extrusion **[5-1]** and the rearrangement **[5-6]** proved to be very similar with the [2+3] extrusion being 0.5 kcal/mol lower in energy. For the rearrangement **[5-6]** a small energy advantage of 1.5 kcal/mol was observed when cleaving the primary C–O bond compared to the secondary. We also noticed that the oxetane is very stable with a very low energy barrier to the [2+2] extrusion **[6-1]** of 2.2 kcal/mol. The geometries of the transition states **[5-1]** and **[5-6]** are sketched in Figure 7.

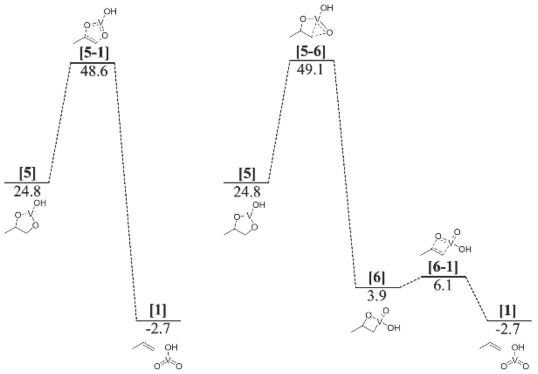


Figure 6. energy barriers for the [2+3] extrusion (left) and the rearrangement followed by a [2+2] extrusion (right).

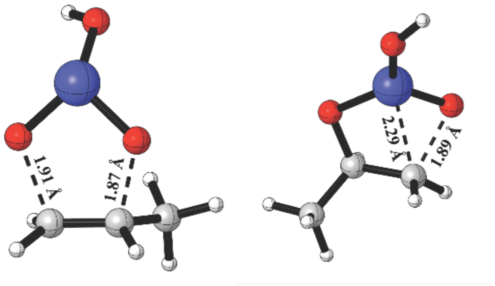


Figure 7. transition state geometries of **[5-1]** (left) and **[5-6]** (right).

From the reduction mechanism, we noticed that all V(III) complexes had the lowest energy in their triplet state – however, for the transition states **[5-1]** and **[5-6]**, a transition state in the triplet state could not be found. This is because the extrusion takes place in a step-wise manner in the triplet state, which causes the C–O bonds to be broken sequentially.[23] The absence of a [2+3] extrusion transition state was identified by the presence of two negative frequencies in the vibrational frequency calculations, for geometries close to other similar transition states (C–O bond distances at 1.8, 1.9 and 2.0 Å). Further calculations showed that the cleavage of one C–O bond lead to the formation of the radical intermediate **[7]*** (Figure 8). This intermediate was more stable in the singlet state due to the possibility for formation of an oxetane (**[6']**), similar to the one seen earlier (a structure non-existent in the triplet state). The breakage of the secondary C–O bond was favored over the primary with a difference of 0.4 kcal/mol. This mechanism has a much lower energy barrier than the classic [2+3] extrusion as shown in Figure 8. The transition state geometries of **[5-7]*** and **[6'-1]** are depicted in Figure 9.

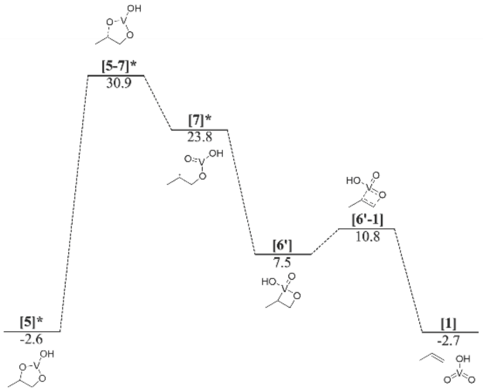


Figure 8. energy diagram for the newly suggested high-spin mechanism for the extrusion step.

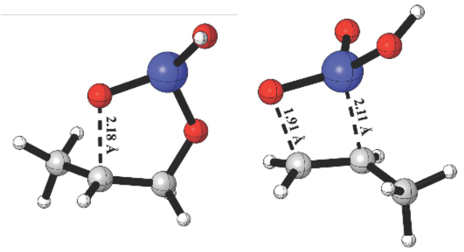


Figure 9. transition state geometries of **[5-7]*** (left) and **[6'-1]** (right).

From the energy diagrams, we can see that the sequential breakage of the C–O bonds gives a pathway favored by 17.7 kcal/mol compared to the **[5-1]** extrusion, with the energetic advantage mostly arising from the high stability of the triplet state **[5*]** compared to the singlet state **[5]**. This confirmed not only a more favorable pathway for the extrusion step, but also a mechanism different from the ones suggested for the rhenium and molybdenum analogues of this reaction.[21,20]

The Rate-Determining Step. Although a lowest energy mechanism could be established for the vanadium-catalyzed DODH reaction, the overall rate-determining step was hard to pinpoint due to the close energy of the two possible reduction steps and the C–O bond cleavage (29.0, 30.9 and 30.9 kcal/mol, respectively). As mentioned before, we observed a slight advantage when reducing the vanadate moiety before condensation with the diol; this energy difference was however very low. Since the V-catalyzed DODH reaction is carried out at very high temperatures, we wanted to inspect the entropy influence on these reaction steps. This was accomplished by calculating the Gibbs free energies of the three high-energy transition states at various temperatures from 300 K to 600 K, and observing the changes in Gibbs-Free Energy. A plot of these changes is presented in Figure 10.

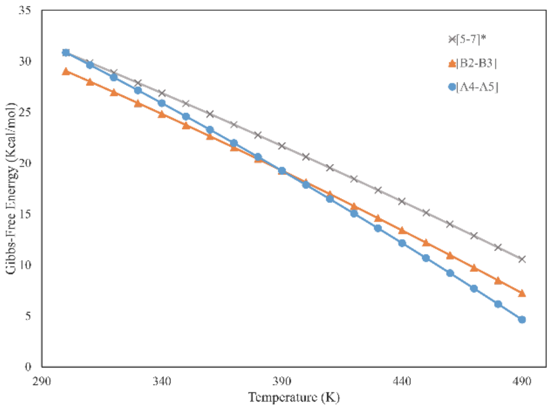


Figure 10. relative change in the Gibbs-Free energy for the highest energy transition states at various temperatures.

As seen in Figure 10, the C–O bond cleavage **[5-7]*** will always be the rate determining step for the reaction, especially when it is taken into account that the concentration of the reductant often exceed that of the substrate diol (e.g. when the solvent *i*PrOH is used as reductant). When increasing the temperature, the reaction pathway of the reduction changes from pathway B to pathway A (Figure 2). This change happens around 390 K, which is below our reaction temperature (above 500 K). In conclusion the calculations seem to favor the formation of diolates **[A3]** which reduces to **[5]***, followed by the single bond breakage leading to the oxetane **[6']** that can undergo a [2+2] extrusion yielding the product alkene and restoring the vanadate catalyst.

Explaining the Selectivity. As shown by the experiments, the vanadium-catalyzed DODH reaction only operates on terminal diols, with little to no reaction occurring for substrates with an internal diol (i.e., having two vicinal secondary alcohols). First, it was examined whether the unreactive substrates exhibited higher transition state energies. All our calculations however, failed to prove this assumption with all energies for the highest transition states showing little to no difference. As seen from the energies presented in Table 6, neither the newly suggested high-spin mechanism, the classic [2+3] extrusion, nor the reduction can explain this selectivity. Only minor differences are observed in the energy barriers for the various transition states relative to the vanadate starting point.

Table 6. Energetic comparison of key transition states with 1,2- and 3,4-hexanediol as substrate.

Transition State	1,2-Hexanediol	3,4-Hexanediol
	kcal/mol	*kcal/mol*
[A4-A5]	11.6	9.8
[5-1]	32.1	30.0
[5-7]*	13.1	12.2
[6’-1]	–11.6	–10.5

Since the explanation for this selectivity could not be found in the mechanism, we decided to examine the differences in binding affinity of the different substrates with vanadium. As seen in Figure 3, only small energy barriers were observed for the binding of diols to vanadium. Meaning, a possible irreversible binding of the diols could lead to a potential “energy sink” which would inhibit the catalyst and increase the energetic span of the reaction. To confirm this possibility, all possible complexes with one or two diols bonded to the vanadium center were optimized (additional diols beyond two per vanadium center proved entropically disfavored, as expected). An overview of these types of complexes is shown in Figure 11.

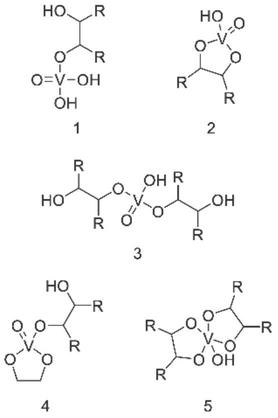


Figure 11. various examined vanadium–diolate complex types.

All possible complexes were built and optimized (only those of lowest energy are shown here – see ESI for the rest). Figure 12 shows the energies of the complexes for 1,2-hexanediol, 3,4-hexanediol and ethylene glycol, the two latter being unreactive.

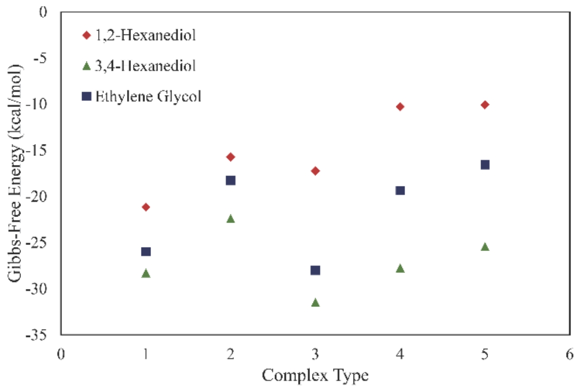


Figure 12. energies of the examined vanadium-diol complexes.

As seen from Figure 12, all 3,4-hexanediol complexes exhibit much lower energies than their 1,2-hexanediol equivalents. Complex type 3 of 3,4-hexanediol is 10.3 kcal/mol lower in energy than the lowest energy complex of 1,2-hexandiol (complex type 1), which leads to an increase of the energetic span of the DODH reaction of 10.3 kcal/mol, when the more substituted diol is used. We attribute this large difference energetic span as being responsible for the markedly different reactivity of vanadium towards diols that have two secondary hydroxyl groups. As exemplified by the sharp difference observed between the model compound 3,4-hexanediol which is unreactive, and 1,2-hexanediol which gives 48% yield of 1-hexene. For comparison, the molybdenum-catalyzed DODH on 3,4-hexanediol and 1,2-hexanediol in *i*PrOH give 69% and 77% of the corresponding alkene, respectively.[9]

A similar energy sink for ethylene glycol was also observed in complex type 3 and that provides an explanation for the observed lack of reactivity as well as an explanation for the inhibitory effect of ethylene glycol. This also explains why this phenomenon is only experienced with the vanadium-catalyzed DODH reactions, compared to the molybdenum and rhenium analogues. For rhenium[24] and molybdenum,[7] complexes 2, 4 and 5 would be favorable intermediates due to the ability to regenerate an active catalyst through oxidative cleavage of one of the coordinated diols whereas for vanadium this type of reactivity is not observed.

CONCLUSIONS

The vanadium-catalyzed DODH of polyols driven by the oxidation of *i*PrOH to acetone based on cheap and commercially available ammonium metavanadate, NH_4VO_3 was developed. The reaction is carried out in an autoclave at 230 °C. A dramatic difference in reactivity was observed when comparing terminal diols (1,2-decanediol, 51% yield) and internal diols (e.g. 3,4-hexanediol) where the latter was found to be completely unreactive.

We have also proven that the two vicinal hydroxyl groups have to be oriented *cis* to each other for the unreactive diolate complexes to be formed, as addition of *cis*-1,2-cyclohexanediol clearly blocks reaction of 1,2-hexanediol (19% yield) whereas the *trans*-stereoisomer has little to no effect on the reaction (43% yield of 1-hexene). The target molecule glycerol was found to be remarkably unreactive under our the autoclave reaction conditions, though the isopropyl ether analogue, 3-isopropoxy-1,2-propanediol reacted to give good yields (46%).

The original rhenium-catalyzed DODH and the recently developed molybdenum-catalyzed DODH do not differentiate based on diol substitution patterns, which warranted an in-depth theoretical study employing density functional theory (DFT) calculations. The dramatic difference in reactivity was found to be rooted in creation of too stable complexes between the substrate internal diols and the vanadium center that hinders efficient catalysis. The same explanation clarifies, why the addition of ethylene glycol inhibits the reaction of otherwise reactive diols and the good correspondence between experiment and theory will prove useful in the development of new and more efficient DODH technologies.

EXPERIMENTAL SECTION

Reaction Conditions A. Forty millimoles of diol, 2.0 mmol of catalyst (5 mol%, calculated with respect to the amount of vanadium), 500 mg of hexadecane (internal standard), and 100 mL of solvent (isopropyl alcohol) were mixed in a 300 mL PTFE cup and placed in a 400 mL Berghof autoclave with a magnetic stir bar (500 r.p.m.) and computer-controlled heating plate. The autoclave was sealed, pressurized with 15 bar of N_2 or H_2, and heated to 230 °C for 1000 min; the temperature typically stabilized between 225 and 230 °C, while the maximum pressure was 50–70 bar. When the system had cooled to room temperature, the pressure was released, and the reaction mixture was filtered to remove a fine, black precipitate and analyzed by GC (for determination of conversion and yields) and GC-MS (for observation and identification of other products).

Reaction Conditions B. The experimental setup was identical to that in Reaction Conditions A except for the following changes: The reactions were conducted on half scale in a 150 mL Swagelok cylinder, which for 1020 min was placed in an aluminum block that had been preheated to 250 °C. Neither the temperature nor the pressure could be monitored in this experimental setup.

Computational Methods. DFT calculations were performed in Jaguar[25,26] with the B3LYP functional[27,28] with added D3 corrections.[29] We used the LACVP** basis set, which applies the Hay–Wadt ECP and basis set for vanadium, and the 6-31G** basis set for all other atoms.[30] Transition states were found by either a quadratic synchronous transit (QST) search[31] or the standard transition state search incorporated in the Jaguar suite. Intermediates were found by minimizing the transition states toward both the expected starting material and the expected final product, confirming the correct transition state. All intermediates and transition states were characterized by a full, analytic frequency calculation at 293.15 K that resulted in only positive frequencies for intermediates and exactly one imaginary frequency for transition states. Examination of the Gibbs-Free energy dependence on temperature, single point energy calculation with analytic frequency calculations in gas phase were carried out at temperatures between 300K and 600K with increments of 10 K. All transition states involving a proton transfer were modeled both as a direct transfer and as a transfer mediated through a water molecule. The transition state of the lowest energy is shown and the rest can be found in the supporting information. Approximate Gibbs free energies in the solution phase (G_{solv}) were obtained through addition of total Gibbs free energy and the solvation energy ($E_{\text{SCF,solv}} - E_{\text{SCF,gas}}$) obtained through a single point energy calculation with the Poisson–Boltzmann solver (PBF)[32,33] using standard parameters for methanol. The computational model system was kept neutral to avoid complications when comparing charged and neutral species computationally.[34] We do not rule out the possibility of charged molecular species but rather suggest the neutral complexes treated in this work to be suitable computational models of the actual complexes. Visualization and comparison of structures were performed in Maestro.[35] The structural figures in the article were created with CYLview using the POV raytracer for rendering.[36]

ASSOCIATED CONTENT

Supporting Information.

Details on the instrumentations. Typical heating profile for the two reaction conditions. Materials and NMR data. DFT structures. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGEMENTS

The research was supported by a Sapere Aude research leader grant (PF) from the Danish Council for Independent Research (Grant no. 11-105487) and the Technical University of Denmark (LBN, Elite PhD scholarship).

ABBREVIATIONS

DODH, deoxydehydration; DFT, density functional Theory; GC, gas chromatography; GCMS, gas chromatography coupled mass spectrometry; FAME, fatty acid methyl esters.

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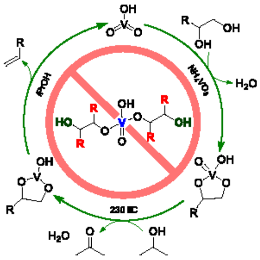

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